Numerical Weather Prediction

Simulations of extreme rainfall events using the Unified Model with a grid spacing of 12, 4 and 1km.

Modelling Extreme Rainfall Events project – stage 1 report
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1 Introduction

This is the first interim report to be delivered from the Modelling Extreme Rainfall Events (MERE) project.

The objective of the project is to investigate the ability of a storm scale configuration of the Met Office Numerical Weather Prediction (NWP) model to predict extreme rainfall events up to 18 hours ahead and to determine what it is about the meteorology of these situations that the model must capture in order to produce useful predictions for flood warning.

The results will be used to identify the ability of a convective scale NWP model to simulate the conditions that lead to extreme rainfall amounts, the nature of the forecast uncertainty for such events and model deficiencies. Recommendations will be made as to how model deficiencies might be overcome and how the output should be interpreted for given situations.

The project follows on from the Storm Scale Modelling project in which it was found that an NWP model with a grid spacing of ~1km has the potential to deliver significantly improved forecasts of convective rainfall events (Roberts 2005). Research has also shown that a kilometre scale model is able to give spatially more accurate forecasts of rainfall enhancement over hills (Lean 2002).

The move towards the use of 'storm-resolving' models has come about as a result of a considerable amount of effort at the Met Office to develop a non-hydrostatic semi-lagrangian version of the Unified Model (UM) (Davies et al 2005). This allows the UM to be run at high resolution with enough speed and accuracy to make the operational implementation of a ~1km forecast model a target for the future when sufficient computer power is available. A 4km version of the model for the UK has recently been implemented operationally. A 1-2km version of the model is planned for 2009/10.

1.1 The purpose of this report

The purpose of this report is to meet the objective of the first stage of the project; to document four extreme events and results from operational forecasts and standard configuration high-resolution simulations. In fact, five cases will be documented.

At this stage, the intention is to get an initial assessment of the behaviour of selected high-resolution simulations (4km and 1km grid spacing) when compared to the operational mesoscale model (12km grid spacing) forecasts. The configuration of the high-resolution models used is the current state-of-the-art recommended by colleagues at the Met Office, Joint Centre for Mesoscale Meteorology (JCMM) from the High Resolution Trial Model (HRTM) project. Sensitivity experiments involving changes to the model parameters or the initial conditions will be carried out in stages 2 and 3. This report aims to provide a basic understanding of the meteorology of the five cases along with the nature of the forecasting issues as a reference for subsequent more detailed study.

1.2 The cases

Five cases have been defined as being extreme for the purposes of this project. They were classified as being extreme either because there was a return period for rainfall accumulations of longer than 100 years (using the Flood Estimation Handbook method) at one or more

locations or a reasonable inference that a 1:100 year event had occurred somewhere on the basis of evidence from the nature of the flooding and measurements from radar. The five cases are listed below:

1. 8th July 2004. Very high rainfall totals at the village of Wittering, Cambridgeshire from a localised thunderstorm that followed a large amount of frontal rain the previous night.

2. 3rd August 2004. Flash flooding in parts of northwest London as a result of intense thunderstorms during the afternoon.

3. 16th August 2004. Very destructive flash flood at the village of Boscastle, North Cornwall from persistent localised thunderstorms during the afternoon.

4. 7-8th January 2005. Flooding in the city of Carlisle, following more than a day of persistent rain over the Lake District and northwest Pennines.

5. 19th June 2005. Flash floods at the villages of Hawnby and Helmsley in North Yorkshire because of torrential rain from a very intense thunderstorm.

Case 1 was a combination of frontal rain and a thunderstorm. Cases 2, 3 and 5 were flash floods from thunderstorms. Case 4 was flooding as a result of prolonged orographically enhanced rainfall.

The description of each of the events makes use of rainfall measurements from gauges and from radar. The radar data have been quality controlled through the Met Office Nimrod system (Golding 1998).

1.3 The NWP models

Forecasts will be presented from three NWP model resolutions on a variety of domains (Figure 1). The three models are described below.

1. The operational mesoscale model. This has a grid spacing of 12km and is run operationally four times a day starting from 00, 06, 12 and 18 UTC (the analysis times). The forecast length is 36 hours. Data assimilation is used to obtain the best starting analysis by incorporating observations into a previous forecast. The domain is shown in Figure 1. Information is passed through the boundaries from the global model (~60km grid spacing) during the forecasts. The forecasts shown in this report have been obtained from the operational archive.

2. The UK 4km model. This has a grid spacing of 4km. The domain is shown in Figure 1. It is now run operationally, but the forecasts shown in this report have been run independently because the cases go back to before operational implementation. Each of the 4km forecasts used a 1-hour forecast from the mesoscale model for the starting conditions. Information was passed through the boundaries from the 12km mesoscale model during the forecasts. For example, a 4km forecast starting at 01 UTC would use fields from a 1-hour mesoscale model forecast that started at 00 UTC and the same mesoscale forecast would supply information through the boundaries during the forecast. For cases 1, 2, 4 and 5 the UK 4km domain was used. For case 3 (Boscastle), a different domain was used (HRTM 4km, orange dashed rectangle in Figure 1). This is for historical reasons because work had already been done on this case.

3. The 1km model (grid spacing 1km). This is not operational. Each of the five cases required a separate 1km domain (coloured squares in Figure 1), because it is too computationally expensive to run at that resolution on a domain large enough to cover all the geographical areas. The domains are 300x300km and positioned so that the area of activity is near to the centre. As for the 4km forecasts, the 1km forecasts used a 1-hour forecast from the mesoscale model for the starting conditions. Information was passed through the boundaries from the 4km (UK or HRTM) model during the forecasts. For example, a 1km forecast starting at 01 UTC would use fields from a 1-hour mesoscale model forecast that started at 00 UTC and the equivalent 4km forecast starting from 01 UTC would supply information through the boundaries during the forecast.

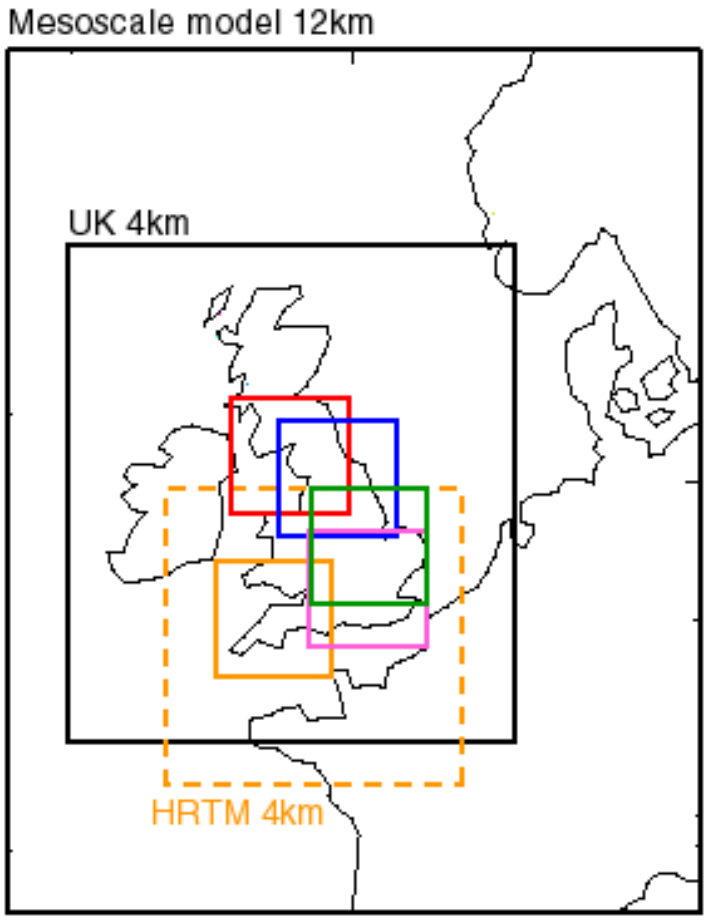

Figure 1. Outer rectangle, operational 12km mesoscale model domain. Inner black rectangle, UK 4km domain. Dashed orange line, High Resolution Trial model 4km domain (used for case 3). Red square, 1km domain for case 4. Blue square, 1km domain for case 5. Green square, 1km domain for case 1. Pink square, 1km domain for case 2. Orange square, 1km domain for case 3.

1.4 Length of forecasts

The objective of this first stage of the project is to obtain a first impression of the performance of high-resolution NWP models for forecast periods of between 3 and 12 hours. The first 3 hours is not of interest here because 4km and 1km models were initiated from 12km model fields and required a period of a few hours to 'spin-up' to the new resolution – particularly for convective events. The exception is the orographic enhanced rainfall case (case 4) which was not convective and thought to be realistic over the first 3 hours. The 12-hour limit is a constraint

brought about by the need to run forecast simulations for all the cases within the time available. It does not mean that longer forecasts are not of interest. In the second stage of the project as the number of cases will be reduced, then longer forecast periods up to 24 hours will also be examined. For that reason, longer forecast periods from the operational 12km model have also been presented here as they were not time-consuming to obtain and will prove useful later. The 4km and 1km forecasts were initiated at either 01, 07, 13 or 19UTC (1 hour after the 12km analysis time) and run for either 6 or 12 hours, with the choice of start time and forecast length dependant on the particular case.

2 Case 1 8th July 2004

2.1 Description of the event

During the 7th August 2004 an area of low pressure moved northwards from Biscay towards the English Channel (Figure 2). On the northern flank of the low an occluded front brought heavy rain during the night of the 7th to the 8th into Southern England and then the Midlands. As the front moved north it slowed down. This allowed a significant amount of rain to fall over parts of the East Midlands. At Wittering (52.62N, 0.48W) 52.6mm of rain was recorded in the 12 hour period between 21UTC on the 7th and 09UTC on the 8th. At nearby Cottesmore (52.73N, 0.65W) 35.8mm was measured over the same period, whilst at Wattisham (52.11N, 0.97E) the value was 36.0mm. During the morning of the 8th the front weakened as it progressed a little further north. Behind the front the clouds broke and allowed sunshine to lift the temperatures enough for showers to break out. Drier air aloft (the so-called dry intrusion) had advected over the region where showers were developing and this caused the atmosphere to become unstable over sufficient depth for the showers to develop into intense localised thunderstorms. The heaviest storms were scattered over the same area where the front had brought the most rain the previous night. A further 51.0mm was recorded at Wittering over 2 hours from 13UTC to 15UTC on the 8th from one of these downpours. In total 107.4mm was recorded over the 19 hour up to 15UTC on the 8th. Using the Flood Estimation Handbook (FEH) method this gave a return period of ~150 years. The reason for the high totals at some locations was the slow moving nature of the storms. An eye-witness described the Wittering storm as being very localised. The schematic in Figure 4(b) provides an overview of the meteorology during the afternoon of the 8th.

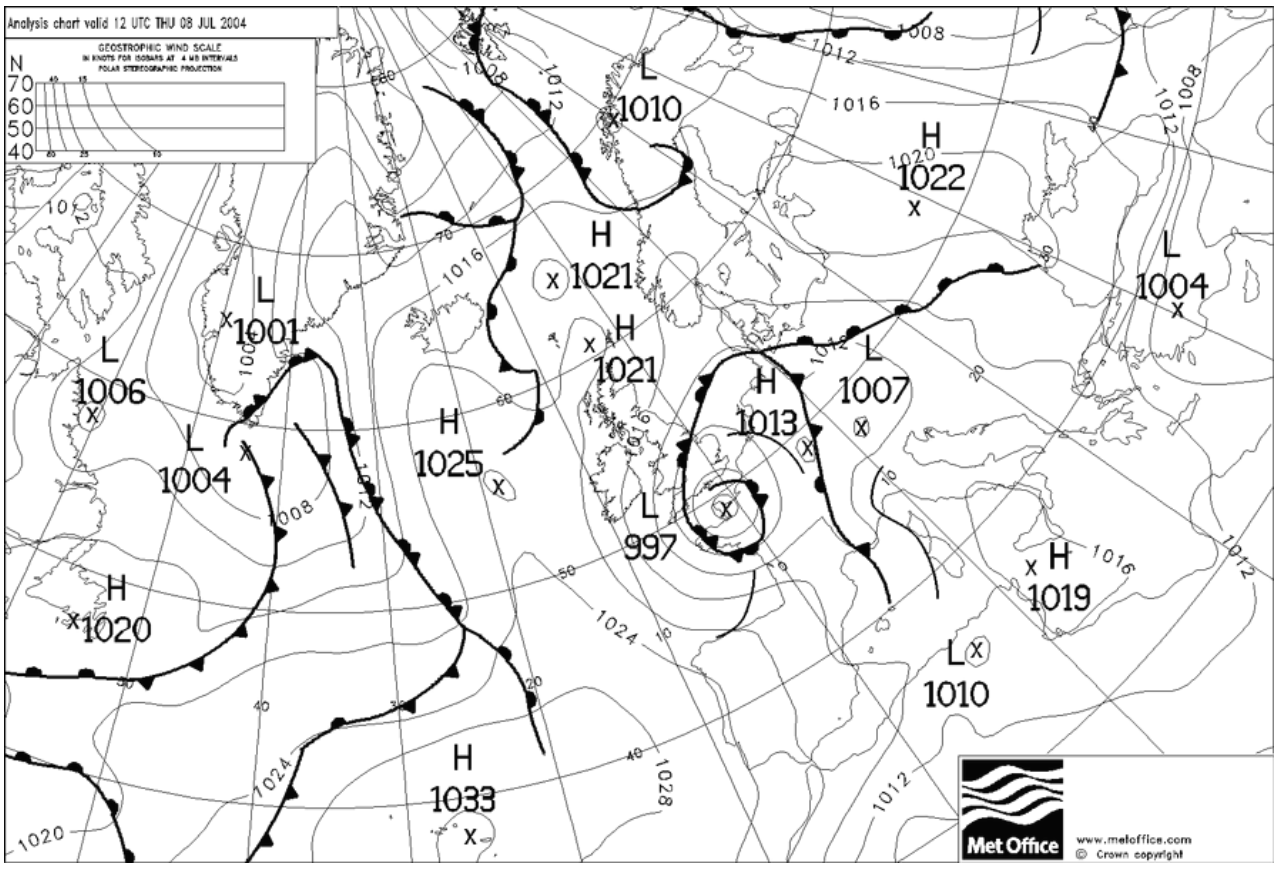

Figure 2. Synoptic analysis for 12 UTC 8th July 2004.

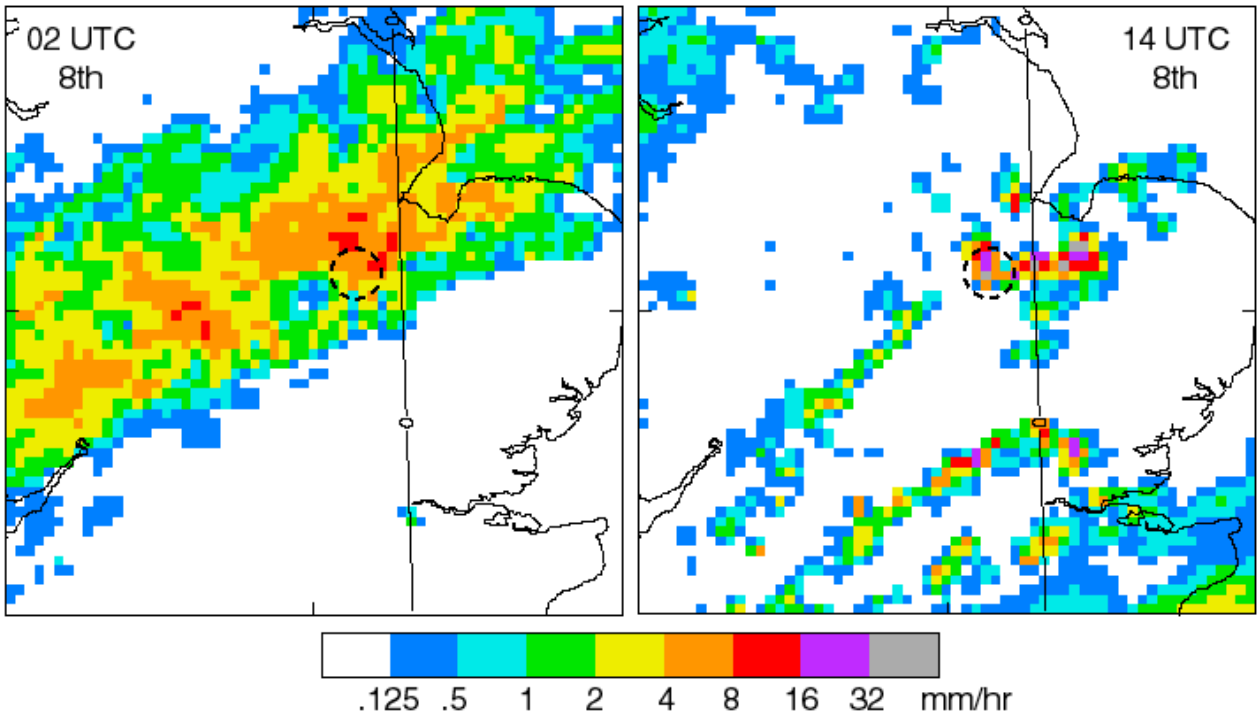

Figure 3. Radar rainfall rates at 02 UTC (left) and 14 UTC (right) 8th July 2004. The 25km-radius dashed circles are centred on Wittering.

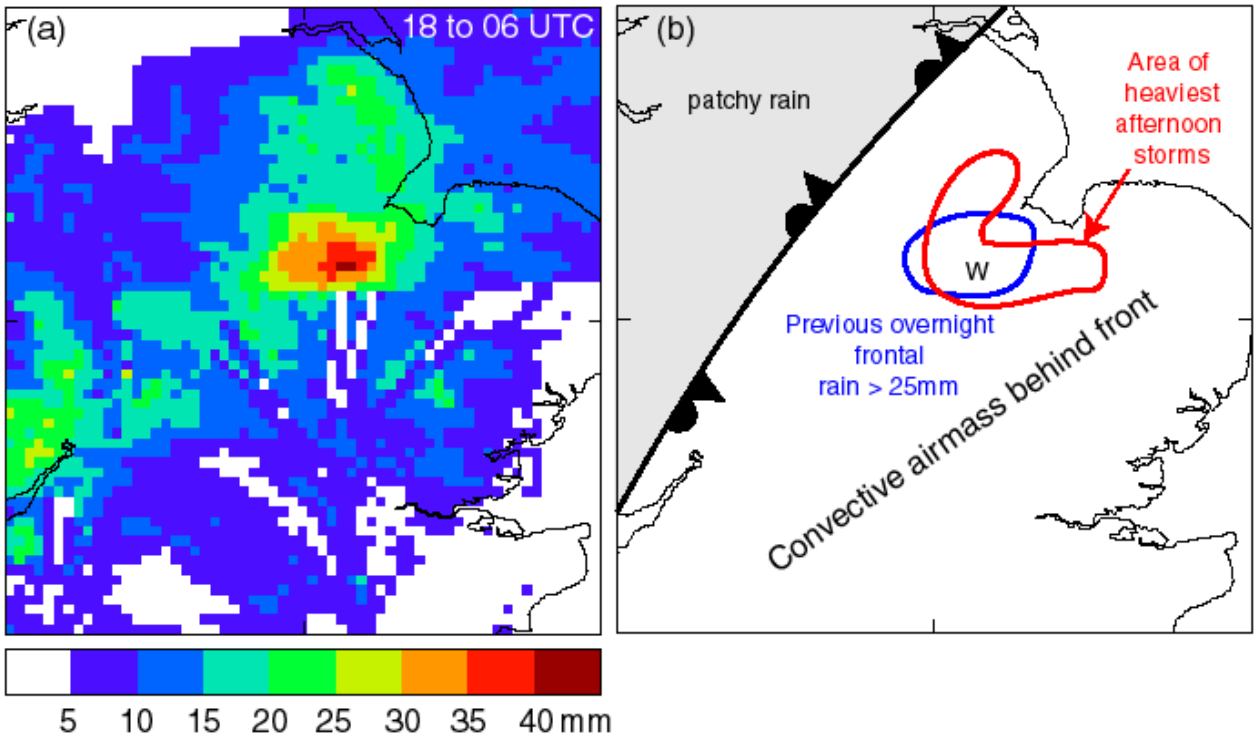

Figure 4. (a) Rainfall accumulations from radar 18 UTC 07/07/04 to 06 UTC 08/07/04. (b) Schematic of the meteorological situation during the early afternoon of 08/07/04. 'W' is the location of Wittering.

The rainfall fell over two periods; frontal followed by convective. It is the combined totals that gave the very large 19-hour accumulation at Wittering, and something of a coincidence that both separate events produced a large amount of rain over the same small area. The frontal rain was not particularly exceptional. Highest radar rainfall rates were only in the range 8-16mm/hour (Figure 3), and this was enough to give ~40-50mm over several hours. The thunderstorms that followed are of more interest because large rainfall amounts fell over a short period of time. For that reason, the focus here is on the second period. Output from the 12km mesoscale model operational forecasts will be shown for both periods. However the 4 and 1km models were only run for the second period to see if it was possible to capture the localised storms.

2.2 Operational forecasts of the frontal rain (period 1)

Figure 5 shows 6-hour rainfall accumulations over the period 21 UTC 07/07/04 to 03 UTC 08/07/04 from four operational mesoscale 12km model forecasts starting at 00,06,12 and 18 UTC on the 7th.

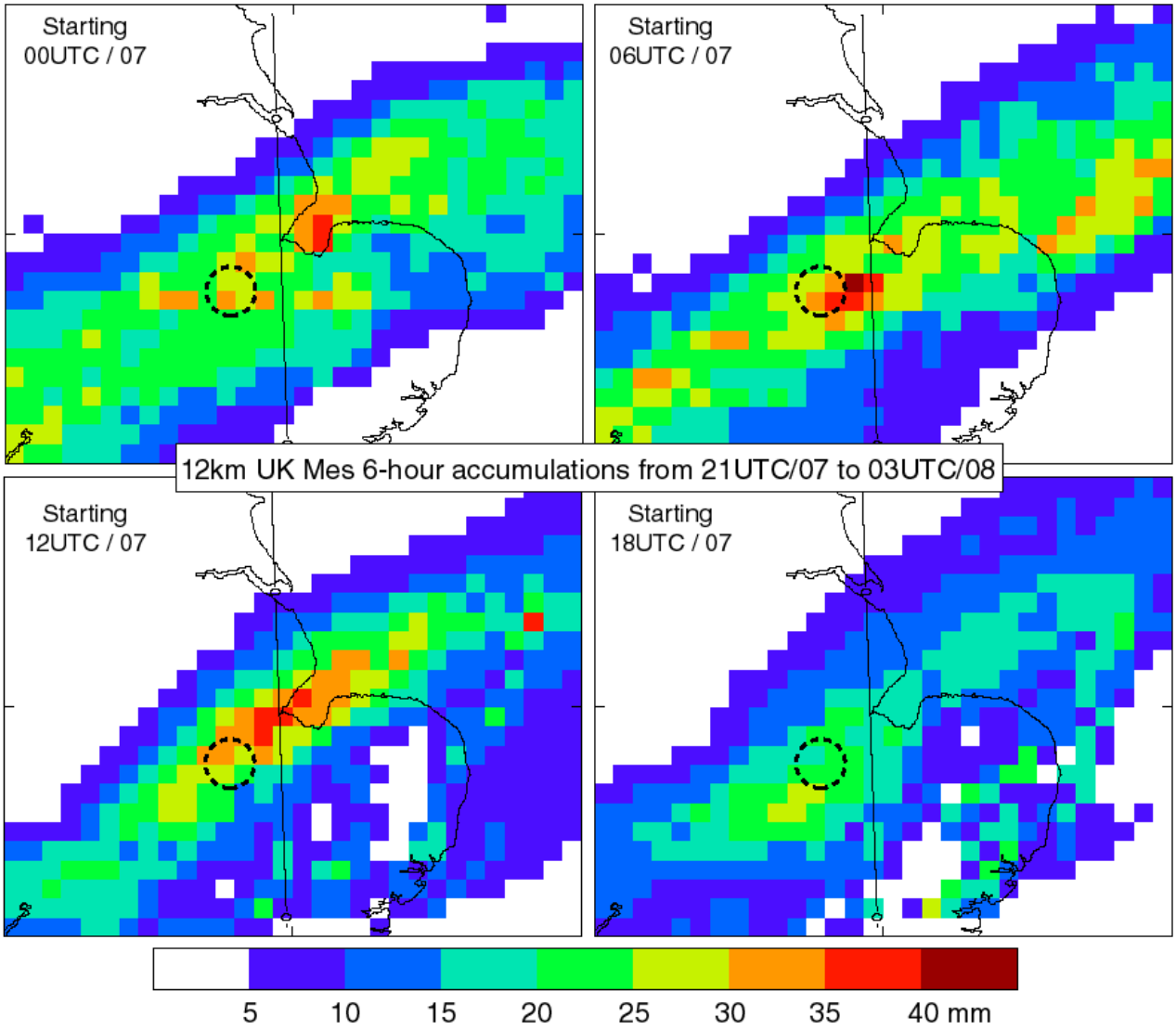

Figure 5. Operational mesoscale model forecasts of rainfall accumulations over the 6-hour period 21 UTC 07/08/04 to 03 UTC 08/07/04. Forecasts started from 00, 06, 12 and 18 UTC 08/07/04. The dashed circle is 25 km diameter centred on Wittering.

All of the forecasts gave a consistent signal for a band of rainfall totals in the range 25-40mm either over or close to the area of interest (dashed circle). Only the most recent forecast gave an under-prediction of ~10mm. The results are a reflection of the fact that the mesoscale model generally does a good job of predicting frontal rainfall if the position of a front is captured accurately – which in this case it was.

2.3 Operational forecasts for period 2 – the thunderstorms

Figure 6 (right) shows rainfall accumulations from radar averaged to the same 12km grid as the operational mesoscale model. The reason for doing this is to allow a direct comparison with the mesoscale model forecasts. When averaged to 12km, the radar accumulations are not large (~13mm in the Wittering area) because the highest totals were concentrated over small areas. This already highlights a problem with trying to predict convective storms using a 12km model. Small showers can not be properly represented on a 12x12km grid square; a convection parametrization scheme is needed to represent the effect of unresolved showers. Even if the model is predicting the correct average amount of rain, it can not give an indication that there may be larger quantities on small scales.

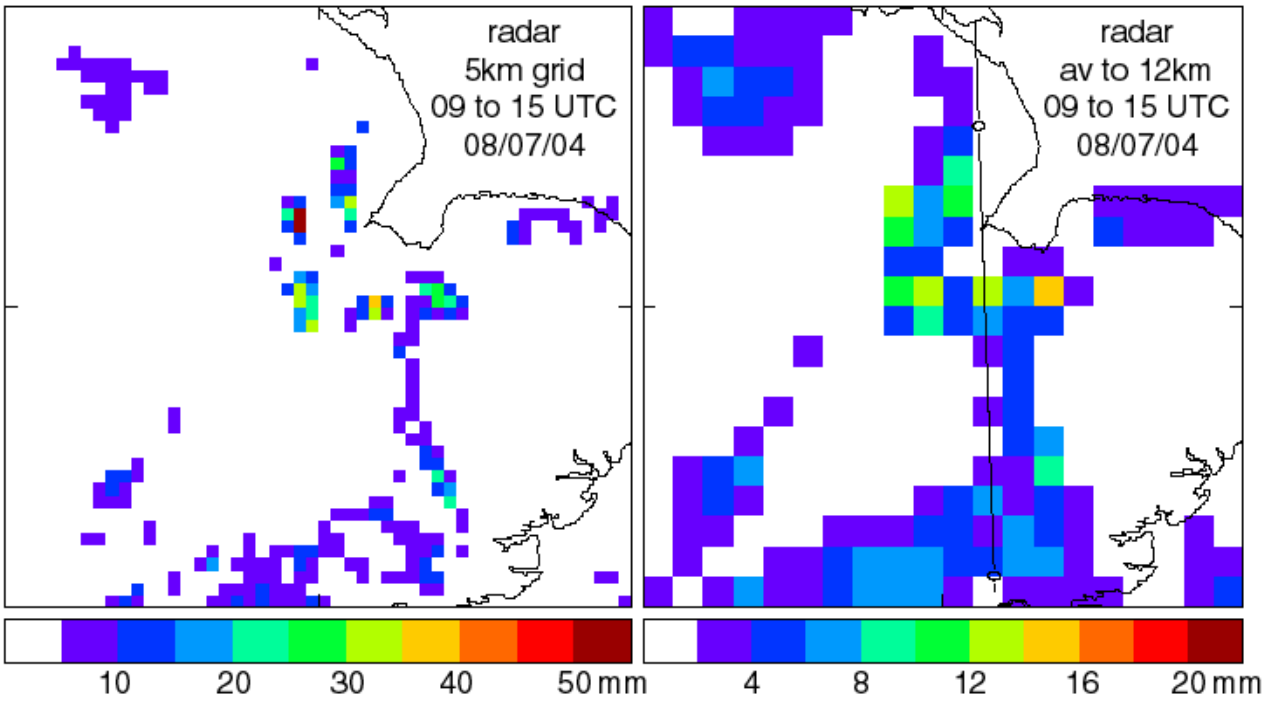

Figure 6. Rainfall accumulations from radar over the 6-hour period 09 UTC to 15 UTC 08/07/04 on a 5km grid (left) and averaged to 12km (right).

The operational 12km forecasts from 12 and 18 UTC on the 7th (Figure 7) did not manage to produce totals greater than 7mm in the Wittering area. They did produce convective rainfall over a wide area and up to 9mm to the west of Wittering. In contrast, the forecast from 00 UTC gave much larger totals, with one grid square > 20mm and quantities close to that observed by radar in the Wittering area. However, the highest rainfall amounts were too large and came from unrealistic single grid square representations of the rain. It is not known at this stage why that particular forecast produced more rain than the others. The forecast from 06 UTC 8th was much the same as those from 12 and 18 UTC (7th) in generating rain that was too light over too wide

an area. The overall impression is that the 12km model produced convective rain over too wide an area in all forecasts and did not give high enough totals in three of the four forecasts. The forecast from 00 UTC on the 8th was the one run that give an indication of the possibility of high accumulations in the correct area, although there was insufficient resolution to capture the localised nature of the showers.

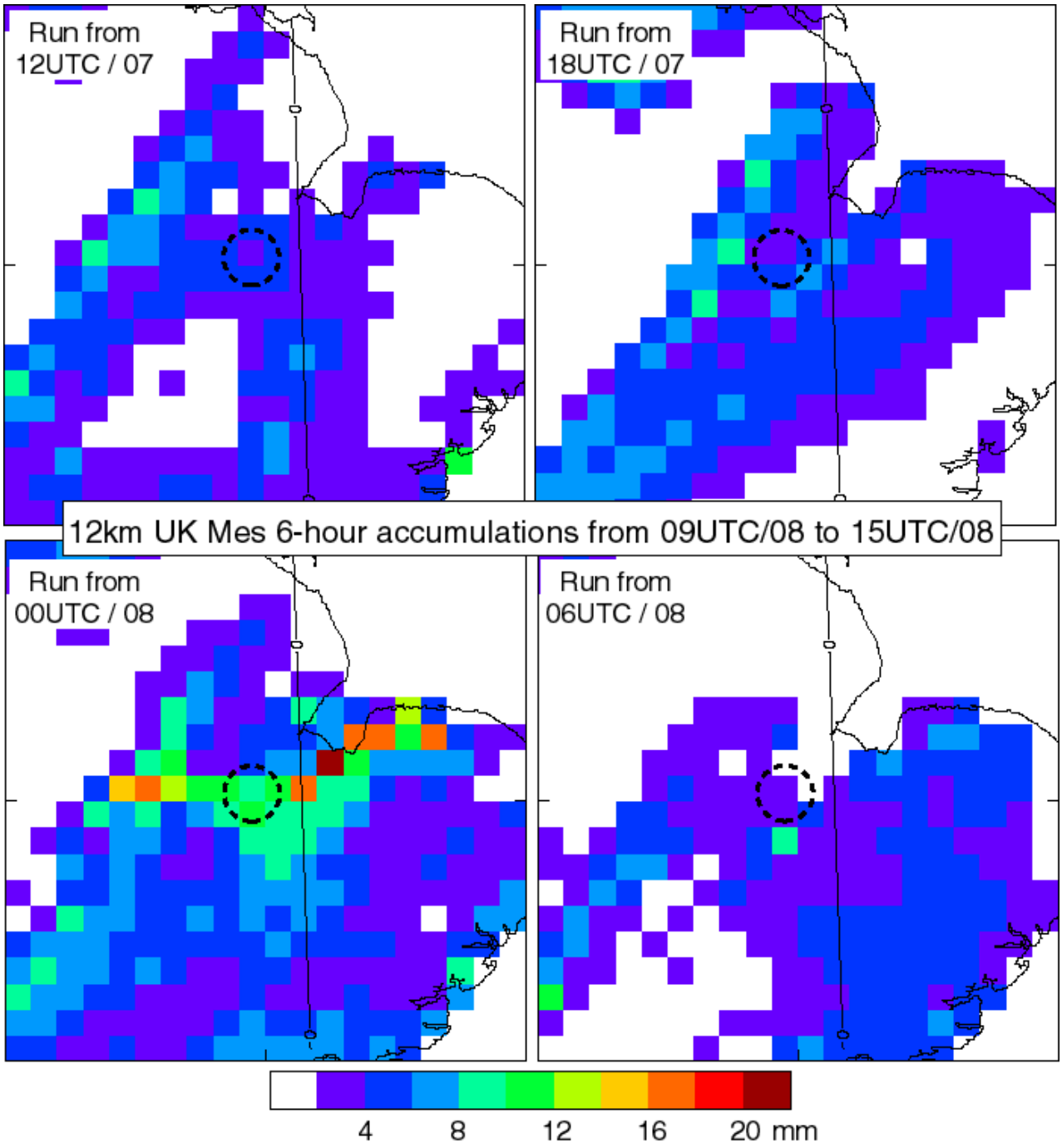

Figure 7. Operational mesoscale model forecasts of rainfall accumulations over the 6-hour period 09 UTC 08/07/04 to 15 UTC 08/07/04. Forecasts started from 12 and 18 UTC 07/07/04 and 00 and 06 UTC 08/07/04. Dashed circles are 25km diameter centred on Wittering.

2.4 High-resolution forecasts

Forecasts were run at 4km and 1km from 07 UTC on the 8th. Figure 8 shows the 6-hour accumulations from 09 to 15UTC that were obtained from each forecast averaged to the 12km grid. The averaging was done to make a direct comparison with the 12km forecasts before looking at the performance of the high resolution output. As was the case in the 12km forecasts the higher resolution simulations produced rain that was too widespread. They also produced totals that were too high compared to radar and higher than the 12km forecasts (in particular the forecast starting from around the same time - 06 UTC).

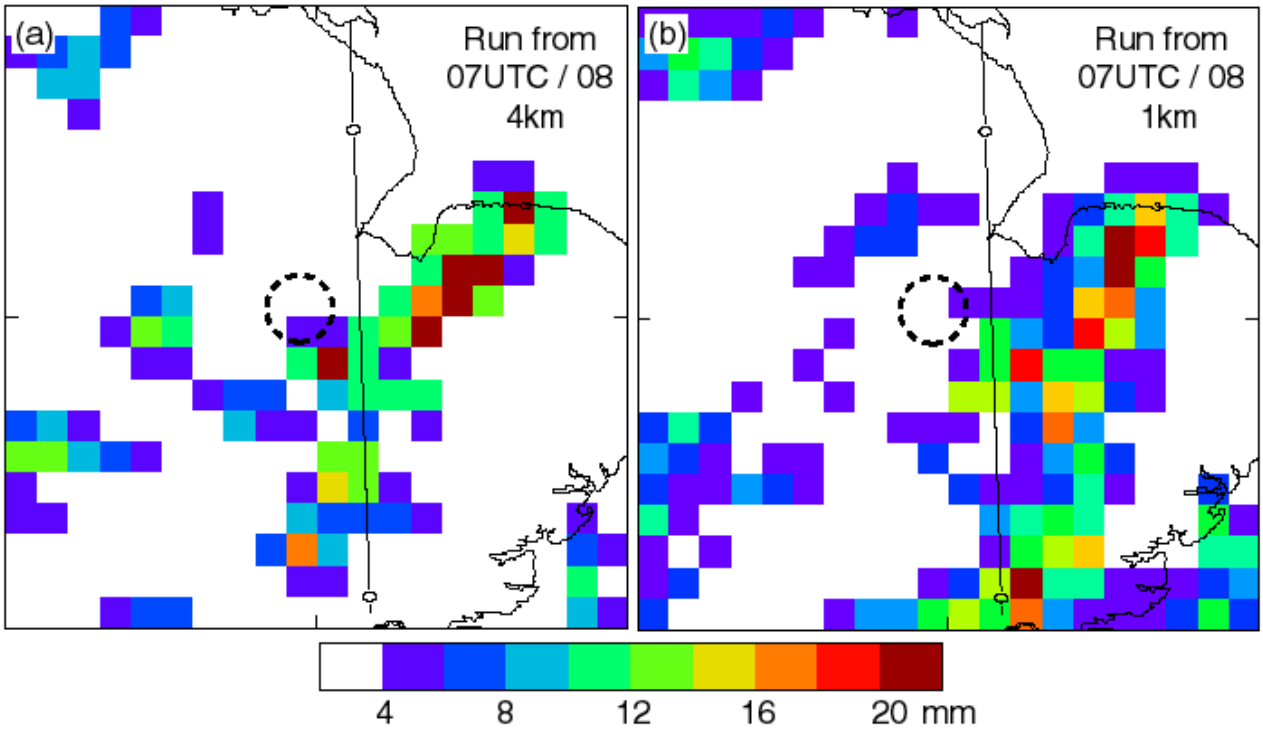

Figure 8. Forecasts starting from 07 UTC 08/07/04 of rainfall accumulations over the period 09 UTC to 15 UTC 08/07/04 averaged to the mesoscale model 12km grid from (a) 4km model (b) 1km model. Dashed circles are 25km diameter centred on Wittering.

The 4km forecast generated several squares over 20mm and the 1km several over 18mm. They both had the showers displaced too far east and south in a band extending into southeast England. It would appear that the increase in resolution from 4km to 1km made little difference to the spatial distribution of the rain on this occasion even though it changed the amounts somewhat. In terms of producing rain in the correct specific locations, the higher resolution forecasts did not improve on the operational forecasts. However, they did give much more of an indication that high rainfall totals were a possibility somewhere in the locality. This is more clearly seen in the output accumulations at the forecast resolution (Figure 9). The 4km forecast produced more than 50-60mm of rain over some grid squares and the 1km forecast more than 40-50mm in places. When compared to radar on a 5km grid, the 4km model probably had peak values that were too high. Some caution is required in making that statement as there are errors associated with radar, but even so, we know that the showers were very localised and quasi-stationary so an accumulation of >60mm over 16km^2 is consistent with point values in excess of 100mm. The 1km forecast, on the other hand, was more realistic but may have slightly under-predicted the highest totals. The reason why the 1km model had too much rain when averaged to 12km is not because the peak values were too high, but because the showers were too extensive.

As well as giving the most reasonable peak rainfall totals, the 1km model developed the most realistic looking instantaneous rainfall. It makes intuitive sense that the two should go together. The realism of each of the forecasts can be viewed in Figure 10. The 12km forecast(s) were unable to produce sufficiently high rainfall rates because of inadequate resolution. This is a standard problem for a 12km model when showers are small. At 4km, reasonable intensities were produced, but the cells were too large and blobby; typical of 4km output for this type of situation. At 1km the showers look realistic, but they had merged into a large blob/band of rain instead of remaining fairly isolated. The reason for this is unknown at present, although a plausible explanation is that because the 1km model generated a rash of individual showers a couple of hours too early, it had more time to merge them into a single entity. Of course, that then begs the question - why the showers triggered so early? Another question worth asking is whether the sea breeze played an important role in this case, and that needs to be examined.

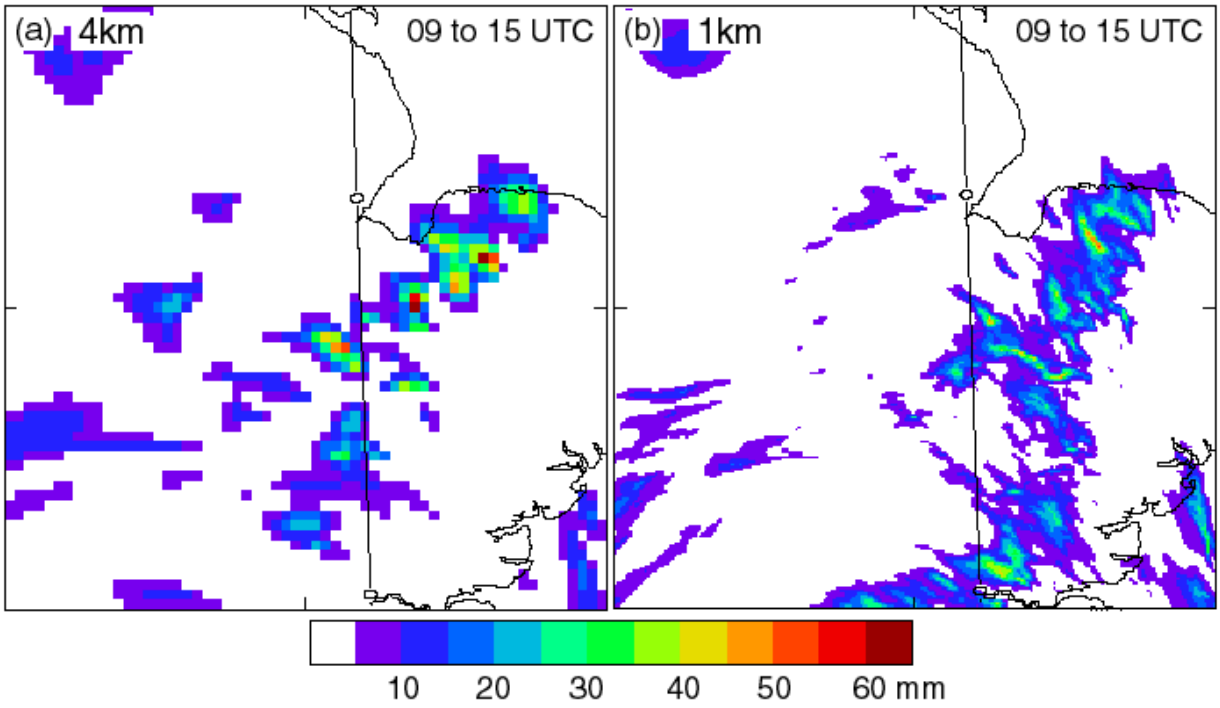

Figure 9. Forecasts starting from 07 UTC 08/07/04 of rainfall accumulations over the period 09 UTC to 15 UTC 08/07/04 from (a) 4km model (b) 1km model.

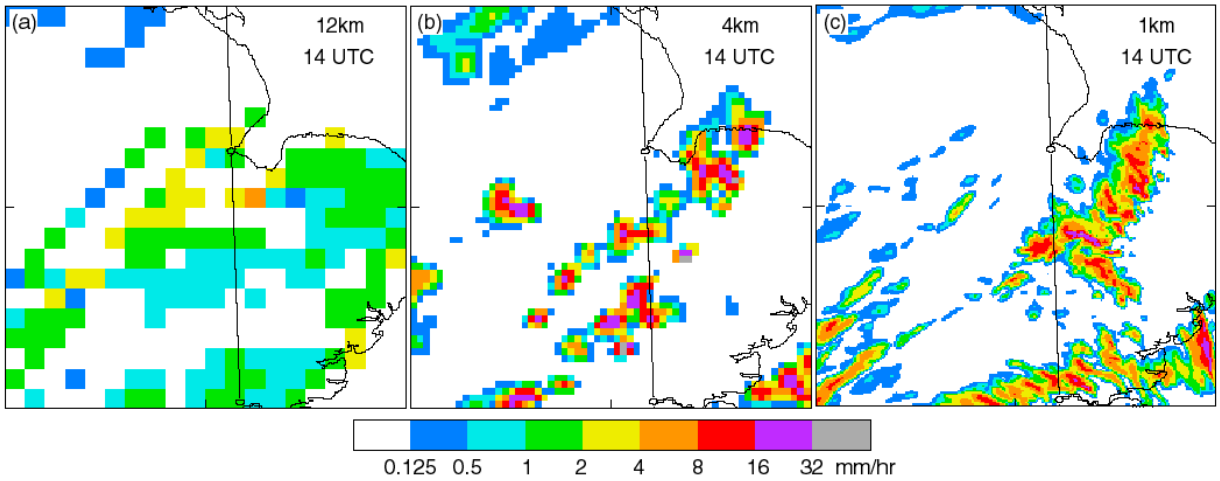

Figure 10. Rainfall rates at 14UTC 08/08/04 from (a) Operational mesoscale model 12km forecast from 06 UTC, (b) 4km model forecast from 07 UTC, (c) 1km model forecast from 07 UTC.

3 Case 2 3rd August 2004

3.1 Description of the event.

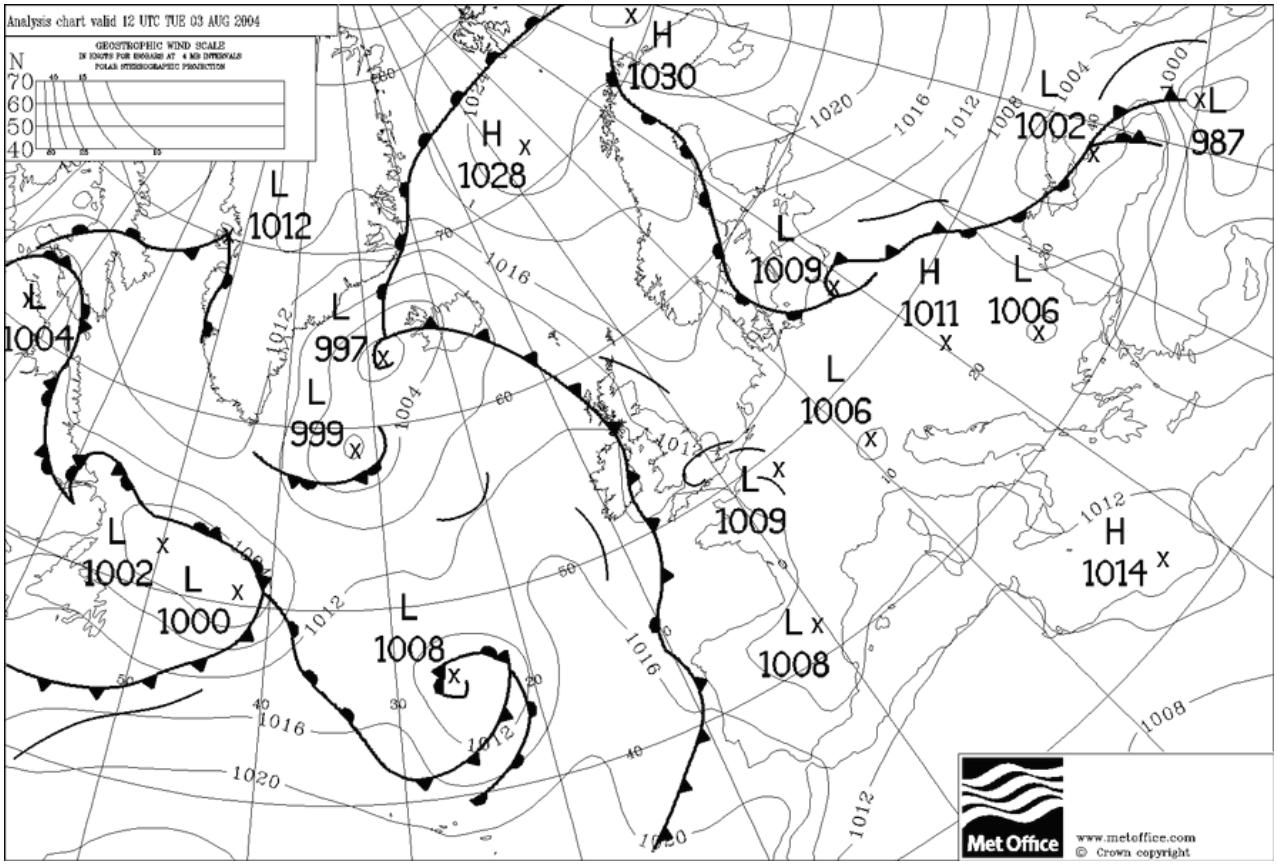

Figure 11. Synoptic chart for 12 UTC 3rd August 2004

The synoptic pattern is shown in Figure 11. Most of the UK was under the influence of hot humid air from the continent. A cold front through the eastern half of Ireland marked the transition between the hot air and cooler air to the west. In the morning and early afternoon an area of thundery rain moved northwards through some western parts of southern England. During the middle of the afternoon heavy thunderstorms developed further east across southern England. These storms organised into a band along the northern edge of an area of rotating dry air aloft (upper-level vortex). This feature has been marked as a trough line on the synoptic analysis (Figure 11). Such features can be identified in water vapour imagery as dark (dry) regions that are seen to rotate and it is not uncommon for thunderstorms to be preferentially triggered in a zone along the forward edge. Once the storms had formed they became intense and progressed north into the Midlands as a band moving in association with the upper-level vortex.

Over and to the west of London another factor came into play. Evidence from numerical model output suggests that a more local convergence line was allowing new storms to initiate on the south-eastern edge of the band even when the main threat of storms should have moved north. These storms too, were very intense and it is the intensity of the rain along with the regeneration of new cells that produced very high rainfall totals and localised flooding. Figure 12 shows a schematic diagram of the meteorology described above. The storms required a combination of

hot moist air at low levels and the upper-level vortex to provide conditions favourable for an area of storms to develop. The convergence line acted to focus and prolong the activity.

Rainfall accumulations from radar are displayed in Figure 13. More than 80mm of rain was measured in parts of northwest London. This was enough to lead to flash flooding and major disruption to commuter traffic. At High Wycombe 42.4mm was collected by a rain gauge in 38 minutes, with peak rainfall rates in excess of 200mm/hour. The value of 42.4mm in an hour gives a return period of ~64 years using the Flood Estimation Handbook (FEH) method. Given that High Wycombe was not in the area of highest accumulations observed by radar, it is likely that more extreme point values would have been obtained in parts of West London if gauge measurements had been obtained.

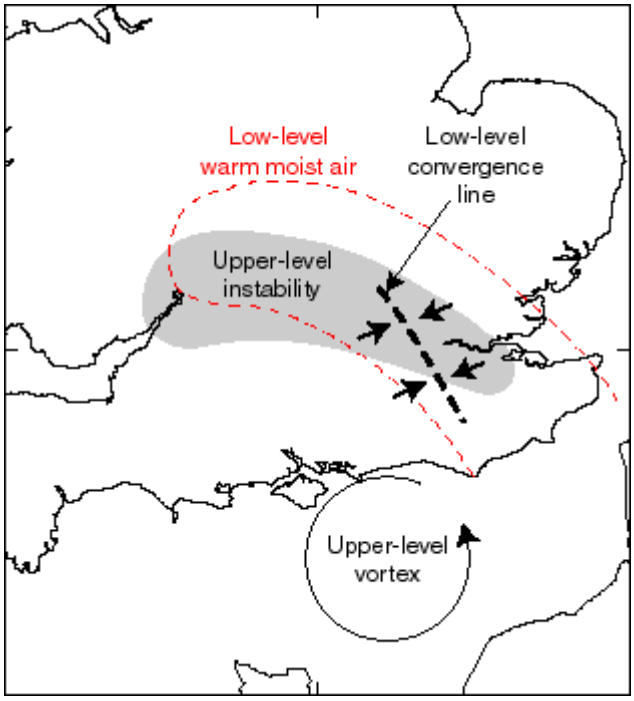

Figure 12. Schematic of the meteorological ingredients associated with thunderstorms during the afternoon of 3rd August 2004. See text for more information.

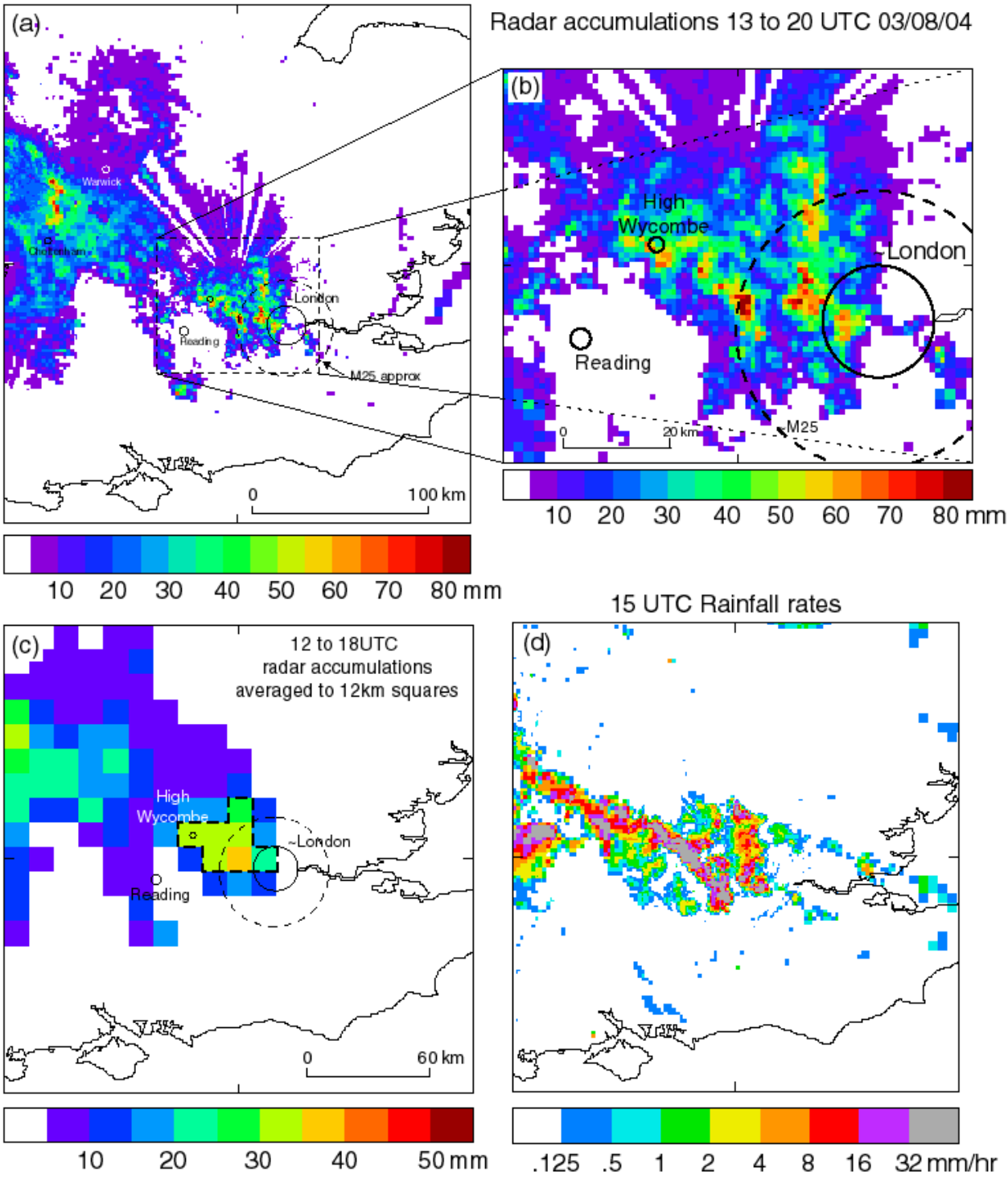

Figure 13. (a & b) Radar accumulations for the period 13 to 20 UTC 3rd August 2004 over Southeast England and a smaller sub area (1km resolution over sub-area). (c) Radar accumulations over the period 12 to 18 UTC averaged to the operational mesoscale model 12km grid. The dashed line encloses accumulations > 20mm. (d) Rainfall rates from radar at 15 UTC on a 1km grid over the area of interest.

3.2 Operational model forecasts

The operational 12km forecast accumulations over the period of interest shown in Figure 14 can be compared like for like with the radar accumulations averaged to 12km shown in Figure 13(c). The 12km-averaged radar measurements gave a highest value of ~37mm over northwest London.

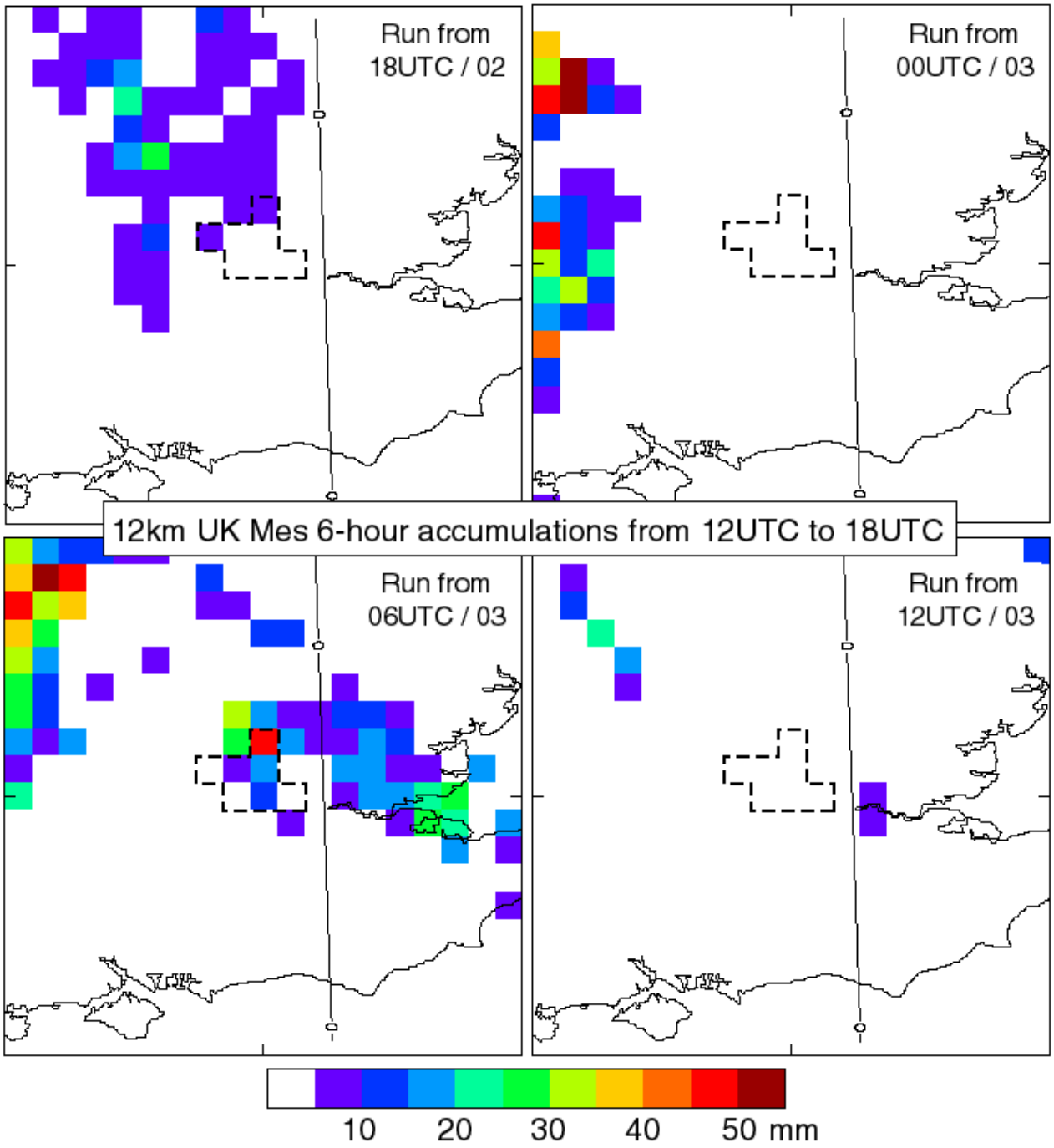

Figure 14. Operational mesoscale model forecasts of rainfall accumulations over the 6-hour period 12 UTC to 18 UTC 03/08/04. Forecasts started from 18 UTC 02/08/04 and 00, 06 and 12 UTC 03/08/04. The dashed line encloses radar accumulations > 20mm (from Figure 13(c)).

Neither of the operational 12km forecasts starting from 18 UTC on the 2nd or 00 on the 3rd gave any signal for significant rainfall in the London area. The high accumulations were either 100km to the west or 50km to the northeast. The reason for the poor performance of the forecasts was that the upper-level vortex was not captured properly. Good forecasts depend on the mesoscale dynamics being sufficiently correct and in this instance the upper-level vortex was located in a data-sparse area over the Bay of Biscay and not correctly analysed when the forecasts began. In contrast, the forecast starting from 06 UTC did have an upper-level vortex and hence was able to generate significant rainfall accumulations close to where they were observed. Curiously, the forecast that started from 12 UTC (just a couple of hours before the storms developed) did not produce rain of any significance anywhere over southeast England. Why this should be the case needs further investigation, as the correct dynamical ingredients seemed to be in place.

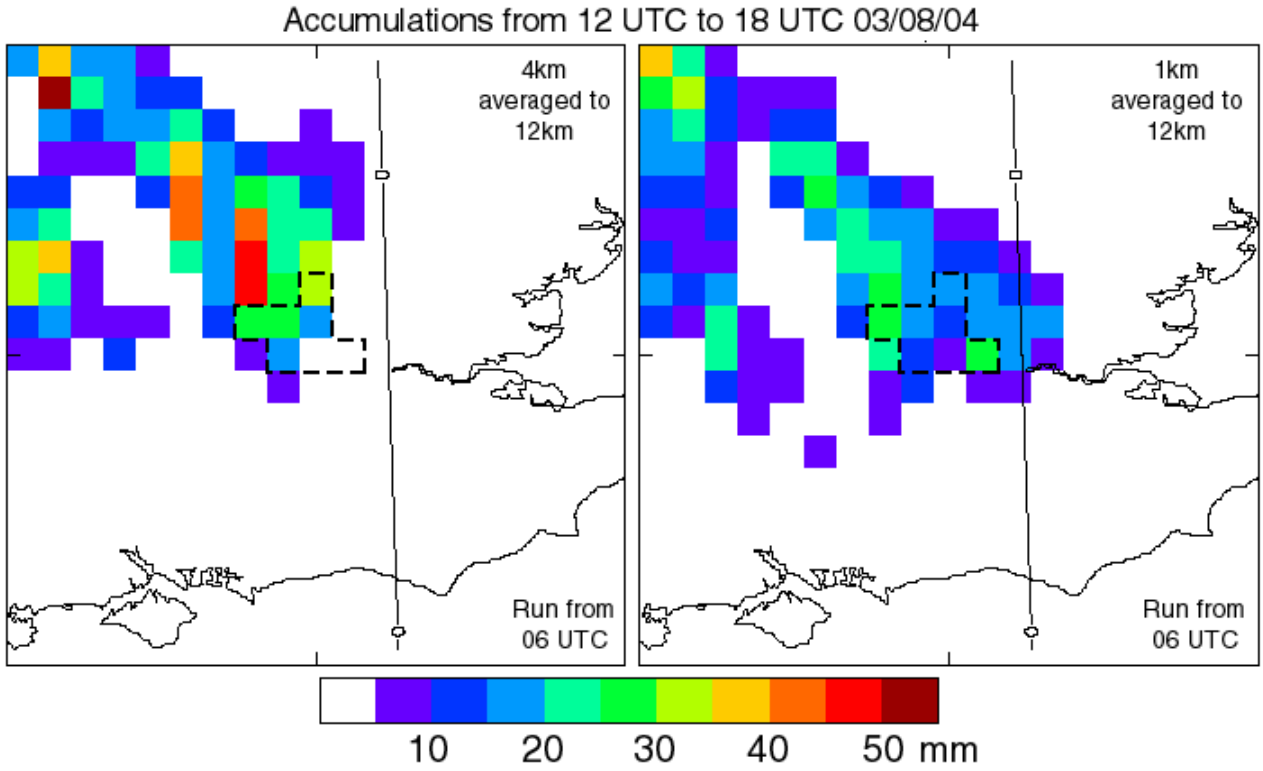

Figure 15. Forecasts starting from 07 UTC 03/08/04 of rainfall accumulations over the period 12 UTC to 18 UTC 03/08/04 averaged to the mesoscale model 12km grid from (a) 4km model (b) 1km model. The dashed line encloses radar accumulations > 20mm (from Figure 13(c)).

3.3 High-resolution model forecasts

Simulations at 4km and 1km were run from 07 UTC. This start time was thought most likely to produce the best results because it used the most accurate12km forecast (from 06 UTC) for the initial conditions. The 6-hour accumulations averaged to the 12km grid are shown in Figure 15. The 4-km forecast was able to produce 12km-averaged totals exceeding 25mm within the area where the highest values were observed, but the main focus of activity was located 20-60km to the northwest. The highest values were too large (>45mm) because some individual cells became too large and intense. The 1-km forecast produced the best spatial distribution of the higher rainfall accumulations. However, it did not produce quite enough rain, with the highest values obtained 15-30mm rather than the 30-40mm measured by radar.

The behaviour of the two high resolution forecasts can be seen more clearly from the accumulations at the model resolutions (Figure 16). The 4km forecast produced totals of 60 to 75mm in north-south oriented bands a grid square wide because it was generating very large rain rates at single grid squares. This looks unphysical and was due to the inability of the model to resolve the most intense updraught areas of the storms properly. The 1km model also produced accumulations of 60 to 75 mm, but within a spatial distribution that looks very much like the accumulations from radar, even to the extent of having two localised maxima in locations close to where they were observed. The 1km model was able to generate higher totals over the London area for two reasons: Firstly because the initial cells triggered in the correct area rather than too far north as occurred in the 4km forecast. Secondly, the 1km model had sufficient resolution to re-generate new cells on the south-eastern part of the main band where convective development was more on a knife edge and storms that did develop were severe. This can be seen in Figure 17, which also shows how the 1km model was producing a much more realistic rainfall pattern than either the 4km or 12km forecasts at 15 UTC. The 4km model characteristically produced a few big 'blobs' of heavy rain, whereas the 12km model produced generally lighter rain over a wider area, although with some heavy rain represented (the highest values may be excessive for a grid-square area of 144km^2).

Both the high resolution forecasts from 07 UTC were able to give an indication that flood-producing rainfall totals (>50mm in less than 2 hours) were a possibility in southeast England and the Midlands. The 1km model was able to focus the risk to within 5-15km of where the most intense rain fell. This was probably because of better resolved local dynamics and shower formation. However, the very high accumulations covered too small an area, which can be attributed to a tendency to produce storms that were too small (hence the low 12km-averaged values). The reason why this was the case is not understood at present.

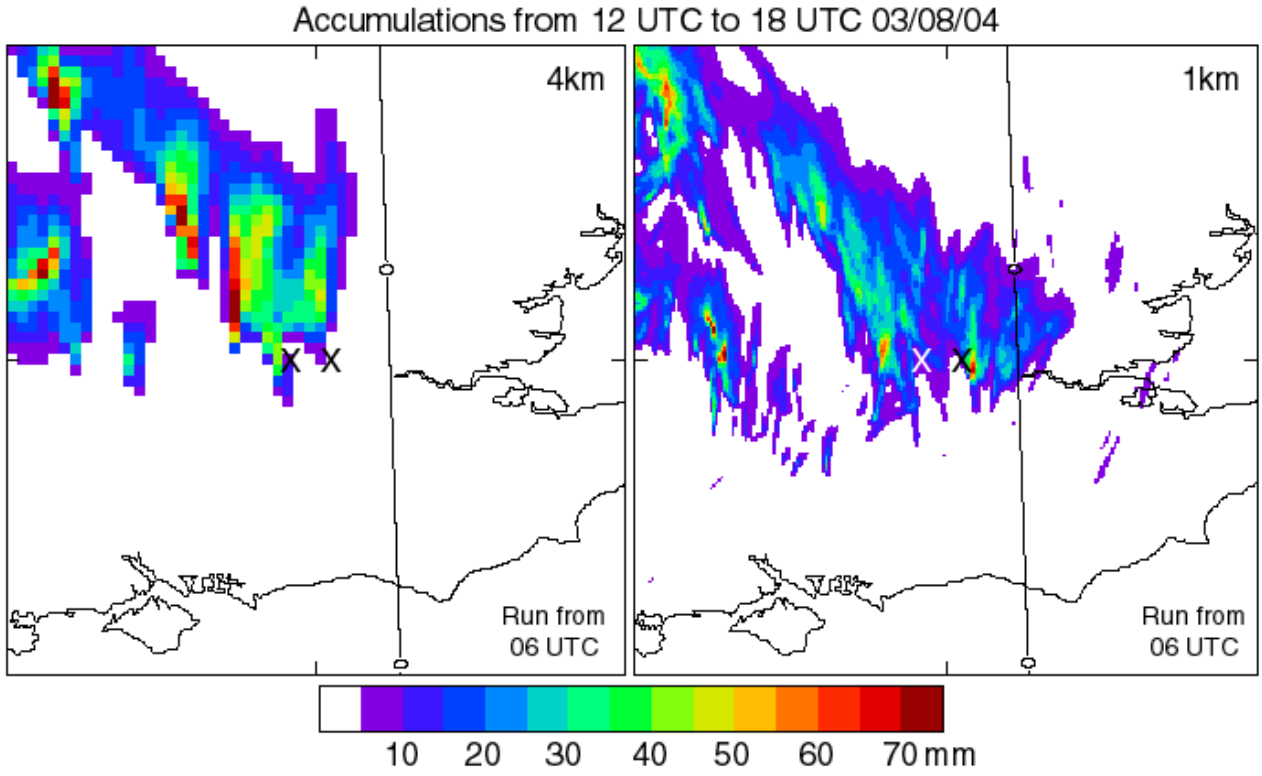

Figure 16. Forecasts starting from 07 UTC 03/08/04 of rainfall accumulations over the period 12 UTC to 18 UTC 03/08/04 from (a) 4km model (b) 1km model. 'X's mark locations of peak accumulations from radar (Figure 13(a)).

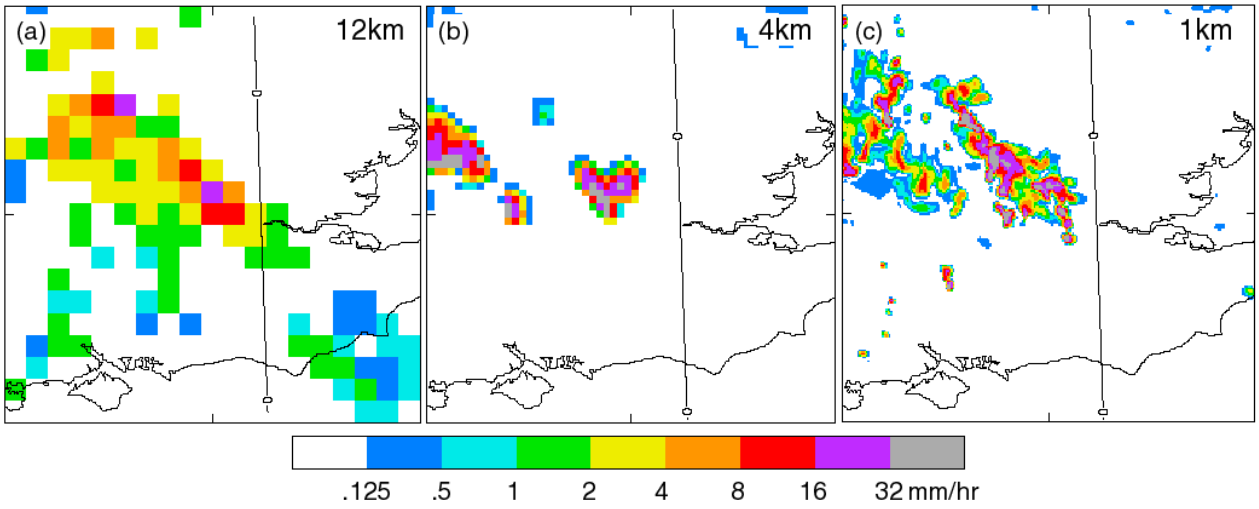

Figure 17. Rainfall rates at 15UTC 03/08/04 from (a) Operational mesoscale model 12km forecast from 06 UTC, (b) 4km model forecast from 07 UTC, (c) 1km model forecast from 07 UTC.

4 Case 3 16th August 2004

4.1 Description of the event

Thunderstorms developed along the north coast of Cornwall during the late morning and into the afternoon of 16th August 2004. During the afternoon a severe flash flood in the village of Boscastle inundated around 60 homes and washed 30 cars into the harbour. A large number of people had to be rescued by helicopter; amazingly, nobody was killed.

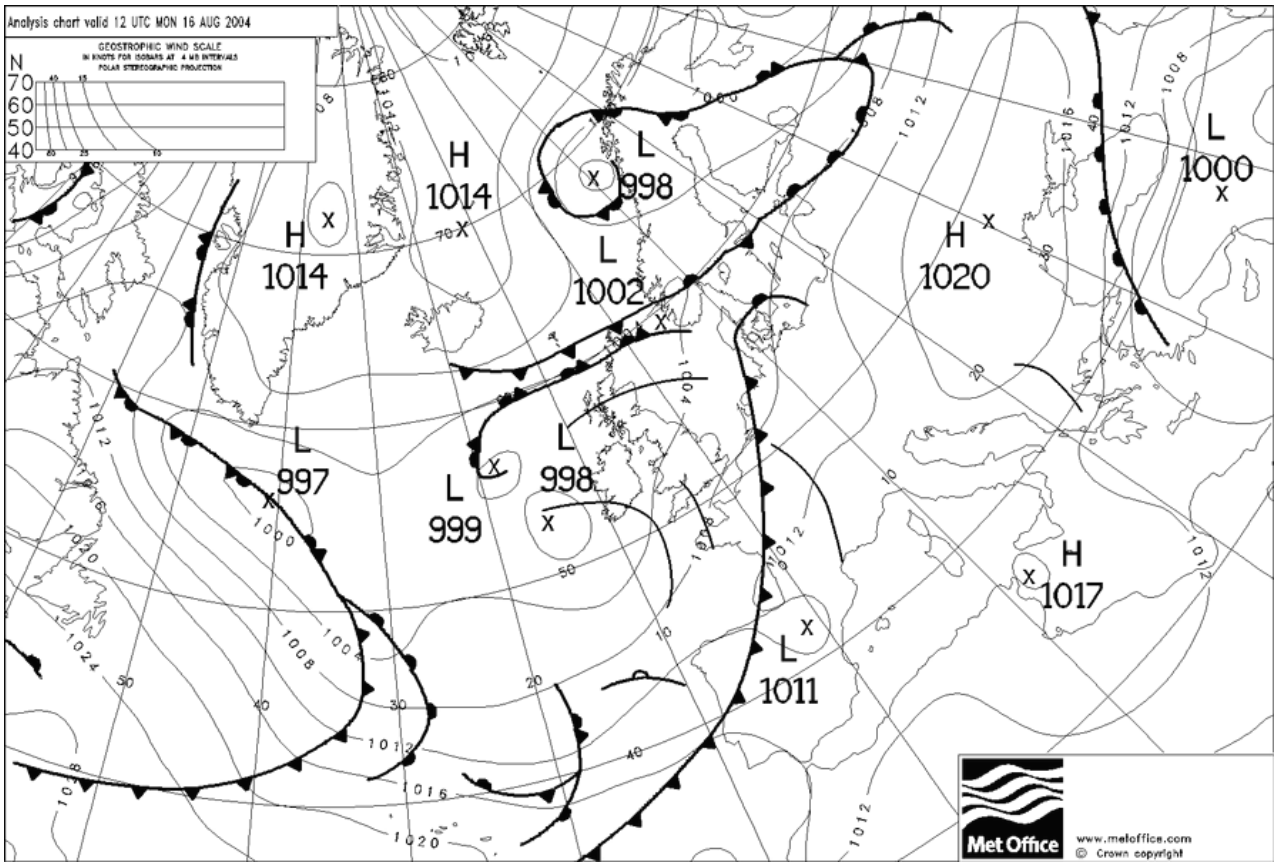

Figure 18. Synoptic chart for 12 UTC 16th August 2004

Figure 18 shows the synoptic pattern at midday (GMT). The southwest of England was under the influence of a south-westerly flow. The near-surface air was not particularly warm or humid; the maximum temperature reached around 21°C, and the wet-bulb potential temperature (θ_w - a combined measure of temperature and humidity) was around 15°C. Typically, the value of θ_w exceeds 17°C when severe thunderstorms occur. During the morning an area of showers had moved through the area in association with 'showery trough A' marked on Figure 21(b), which by early afternoon had transferred into central England. The same trough line is also shown on the synoptic analysis (Figure 18). It could be observed in satellite water vapour imagery as the leading edge of an area of dry air in the mid to upper troposphere – the so called 'dry intrusion', which is often the focus of showery activity. By early afternoon another area of showers, marked 'showery trough B' in Figure 21(b) had reached the southern tip of Cornwall. The area where the flood-producing storms of interest developed was sandwiched between these two troughs in a

region where there was no obvious larger-scale dynamics driving showery activity. The development of the thunderstorms appears to be due to more local effects. The storms appeared to have developed along a line of local convergence that may have been due to the land/sea contrast in the vicinity of the north coast, but the exact nature is not fully understood. What is known is that the individual storm cells kept re-generating at the same location to the southwest of Boscastle before tracking northeast and producing large amounts of rain over the small river catchment just inland from Boscastle before moving off to allow the next cell to repeat the process. See the schematic in Figure 21 and the radar pictures in Figure 19. It was the succession of small but torrential storms propagating over the same location that produced the very high rainfall totals.

The highest recorded daily rainfall amount was 200.4mm at Otterham (Figure 20 (b)). This value has a return period of more than 200 years using the Flood Estimation Handbook method. Nearby at Trevalec 184.9mm was recorded. Radar measurements at 5km resolution gave more than 70mm over a 6-hour period. The discrepancy is mostly due to the large grid size in comparison to the localised nature of the event.

For a much more comprehensive overview of the meteorology, refer to Golding et al (2005).

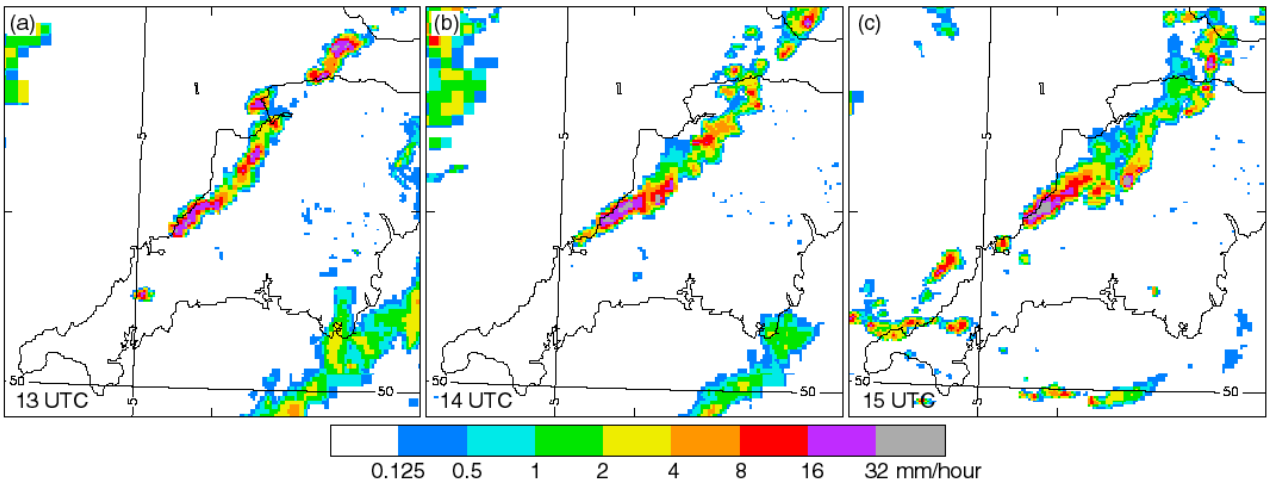

Figure 19. Rainfall rates from radar (mm/hour) for (a) 13 UTC, (b) 14 UTC and (c) 15 UTC 16th August 2004.

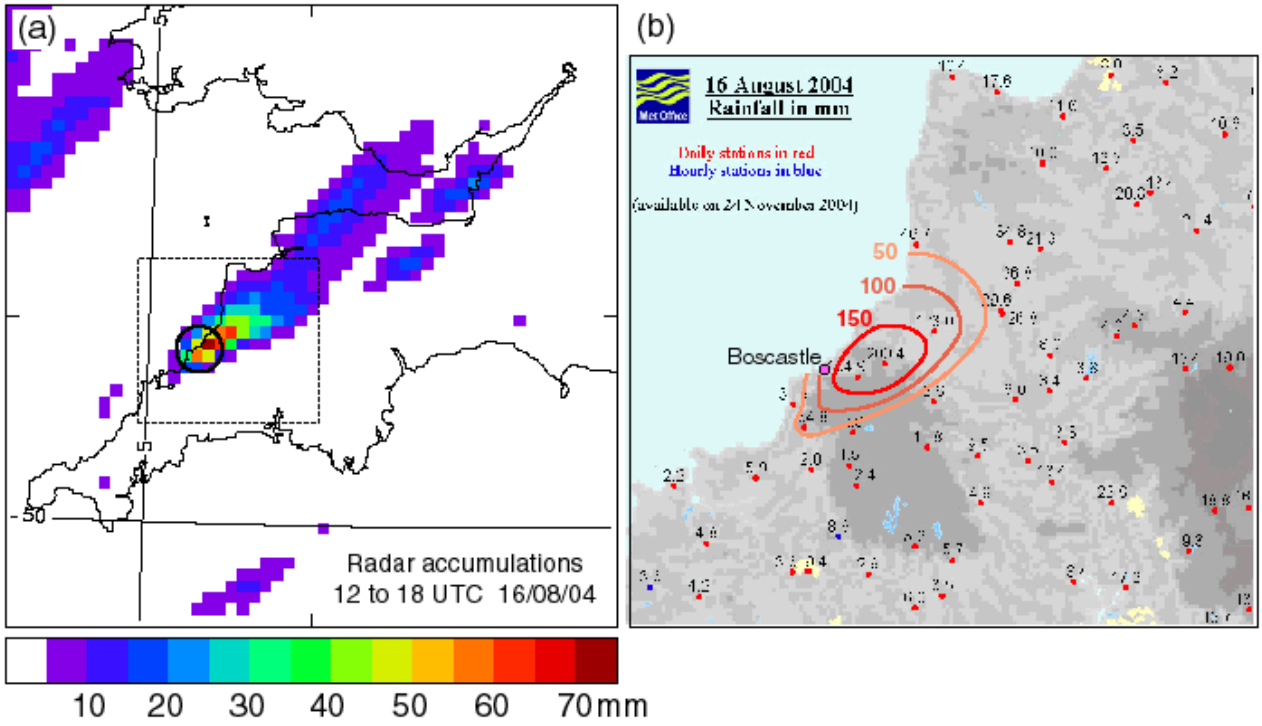

Figure 20. Rainfall accumulations for 16th August 2004. (a) From radar for the period 12 to 18 UTC (b) From rain gauges for the whole day with hand drawn contours for 50, 100 and 150mm. Gauge measurements courtesy of the National Climate Information Centre (NCIC) and the Environment Agency (EA). Circle in (a) is 20km diameter centred at Boscastle.

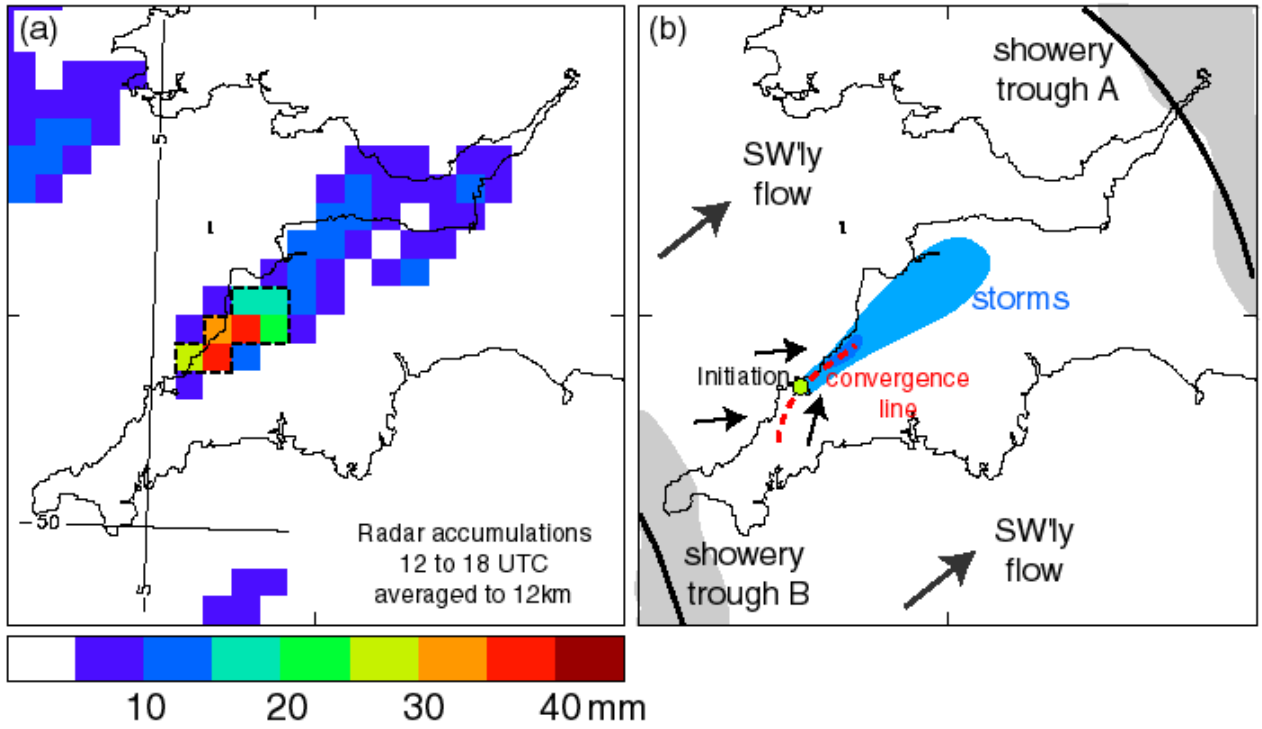

Figure 21. (a) Rainfall accumulations from radar over the period 12 to 18 UTC 16th August 2004 averaged to the operational mesoscale model 12km grid. Dashed line encloses accumulations > 15mm. (b) Schematic of the meteorological situation during the afternoon of 16th August 2004.

4.2 Operational 12km mesoscale model forecasts

Radar accumulations over the period 12 UTC to 18 UTC have been averaged to the mesoscale model 12km grid for direct comparison (Figure 21(a)). The highest 12km-averaged accumulations over that period were between 35 and 40mm. Figure 22 shows the accumulations over the same period from four operational forecasts starting at 18 UTC /15th and 00, 06 and 12 UTC / 16th.

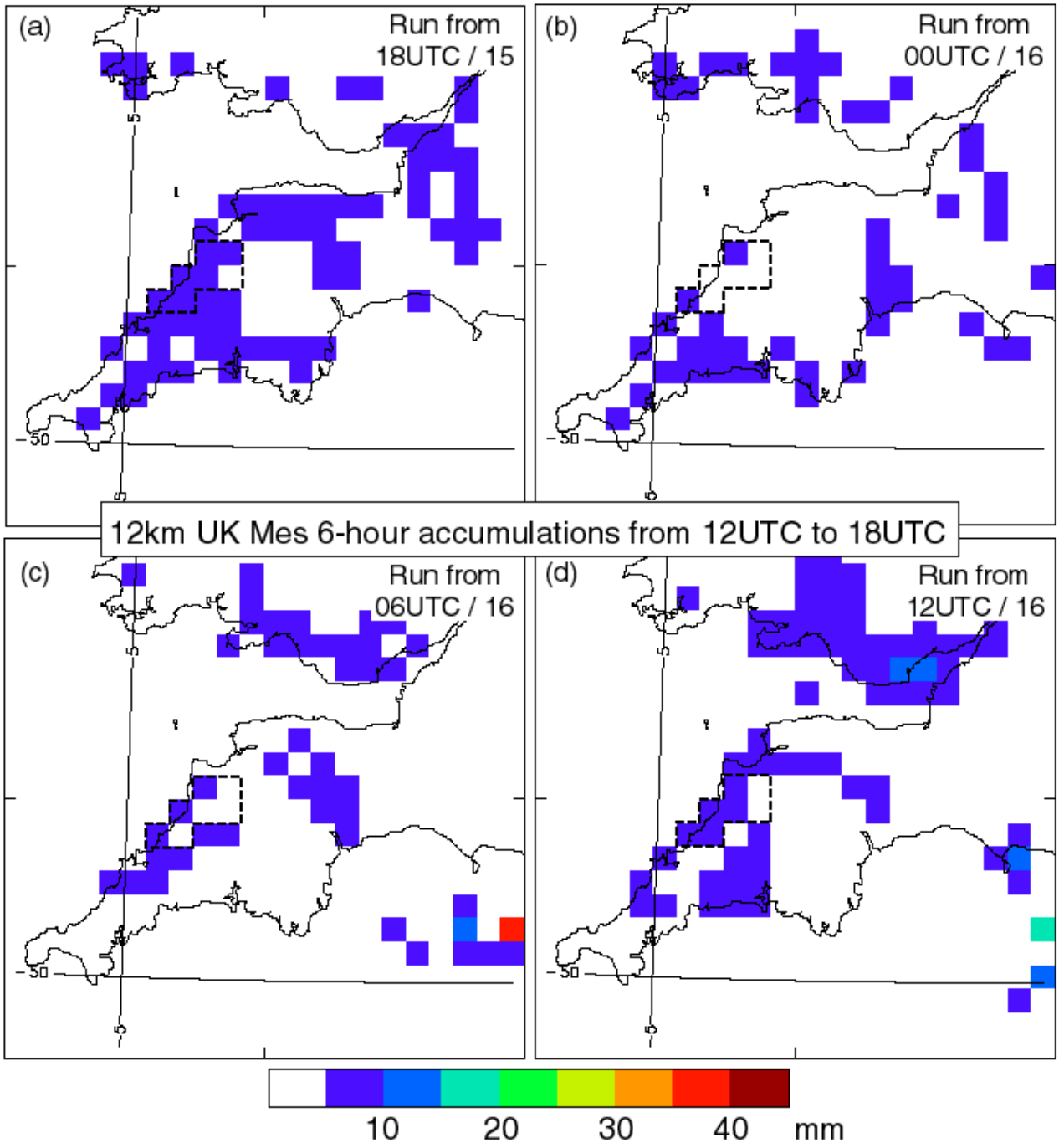

Figure 22. Operational mesoscale model forecasts of rainfall accumulations over the 6-hour period 12 UTC to 18 UTC 16/08/04. Forecasts started from 18 UTC 15/08/04 and 00, 06 and 12 UTC 16/08/04. Dashed line encloses accumulations > 15mm from radar (Figure 21).

Clearly, none of the 12km forecasts have managed to get anywhere near predicting the event. Nowhere over the southwest of England did the predicted rainfall exceed 8mm. It was not that the model failed to capture the larger-scale dynamics sufficiently. It was just unable to represent what happened on the local scale. This is not surprising; a grid length of 12km is too large for storms of that size (<15km across) to be resolved. The model has to rely on a convection parametrization scheme to represent the average effect of unresolved showers. It is unable to represent the storm dynamics or the mechanisms that lead to secondary cell development. However, it does appear to have been able to represent some weak convergence along the north coast with a hint of a line of convective rain in some forecasts, although it also produced convective rain in other areas where there was none observed.

4.3 High resolution forecasts

Figure 23(a & b) shows 6-hour accumulations over the period of interest averaged to the 12km grid from 4km and 1km forecasts that began at 01UTC (starting from 00UTC 12km 1-hour forecast fields). For this case, the 4km model was run over a domain smaller than the UK 4km (see Figure 1).

In contrast to the 12km forecasts, both the high resolution simulations predicted high totals in the correct area (within the black dashed line). The 4km model produced amounts of rain that were comparable to those from radar. The 1km forecast did not generate sufficient rain (peaks of 25-30mm instead of 35-40mm over 12km squares), but the location was almost perfect. Clearly, the higher resolution models were able to represent the mechanisms that were responsible for the formation of the storms at the correct location and were then capable of realistic simulations of the storms themselves. This is particularly true of the 1km model, which produced a line of precipitation that closely resembles the rainfall pattern observed by radar. This can be seen in the 14UTC rainfall rates in Figure 25 and compared with Figure 19. The 4km forecast produced fewer, larger rain areas. This is a typical difference between the two resolutions. Compare them with the 12km model, which was generating rainfall rates that were far too small (1-2mm/hour) from the convection parametrization scheme over too wide an area. Figure 24 reveals that the 4km model generated totals close to those observed by radar, in excess of 70mm over 4x4km squares, but displaced northeast by ~20km. The accumulations from the 1km model were not large enough or extensive enough (>50mm over a few grid squares); however the rain did fall within the correct catchment. The displacement error in the 4km model may be due to the tendency for delayed triggering at that resolution. The reason for underproduction of rain at 1km is not understood. Overall, the high-resolution models were able to give a strong indication that locally very high rainfall totals were possible on that day in the Boscastle area, and with suitable post-processing could have been used to warn of a chance of flooding, even without being able to reproduce the exact nature of the event.

High resolution forecasts from 01UTC are presented here because they gave the most impressive results. Simulations from 07 UTC (not shown) were not quite as accurate (rain shifted further northeast), but were also considerably better than any 12km forecasts.

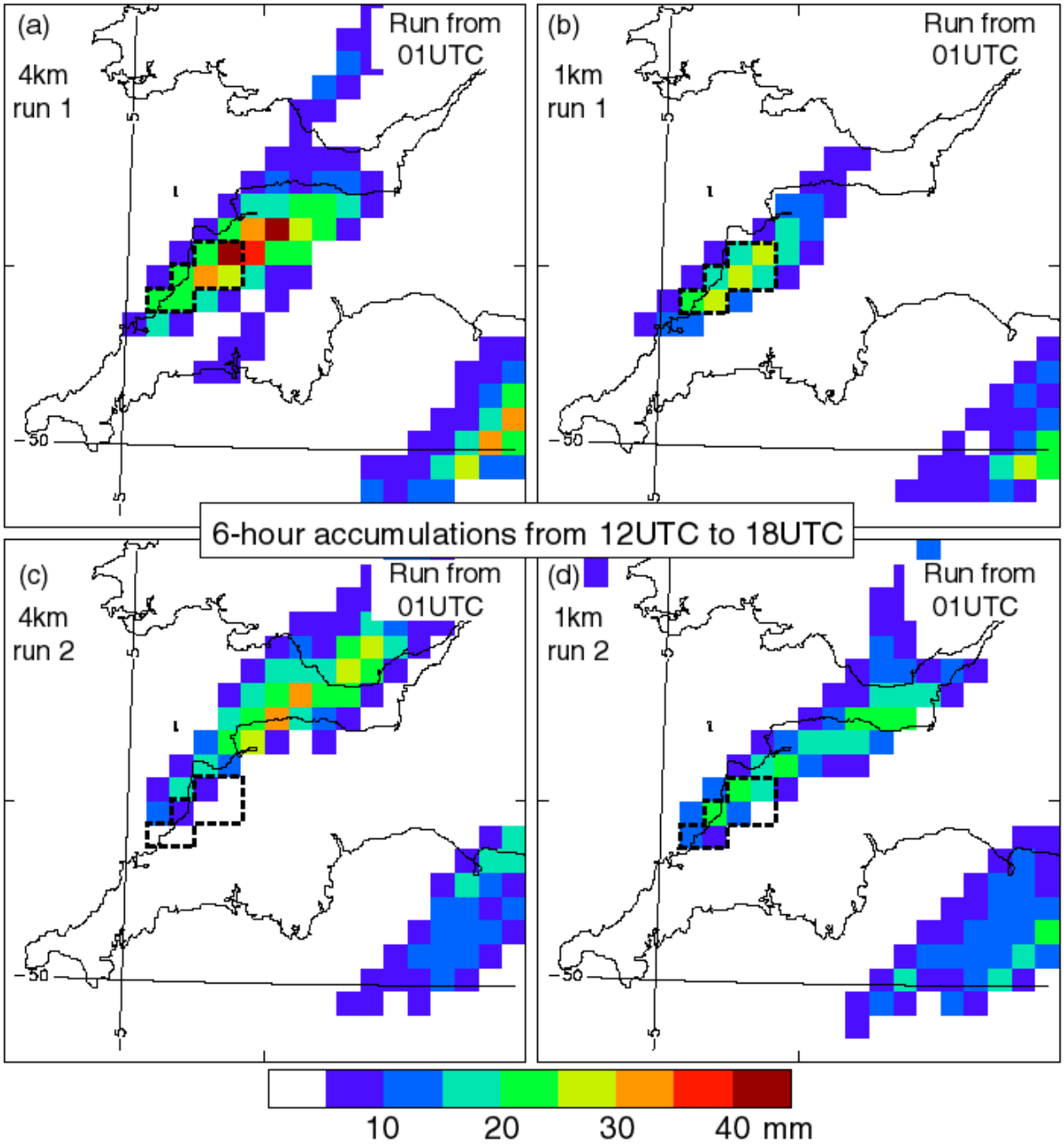

Figure 23. Rainfall accumulations over the period 12 to 18 UTC averaged to the operational mesoscale model 12km grid from high-resolution forecasts starting at 01UTC. Dashed line encloses accumulations > 15mm from radar (Figure 21). (a) 4km without water loading term (see text), (b) 1km without water loading, (c) 4km with water loading and (d) 1km with water loading.

The first high-resolution simulations (run 1) from 01 UTC did not include a term in the model formulation that accounts for the reduced buoyancy in storm updraughts due to the presence of water droplets. This 'water loading' term was included in a re-run of the 4km and 1km models from the same time (run 2). The new predicted rainfall accumulations were noticeably different and are shown in Figure 23(c & d). The highest accumulations were reduced in both forecasts; from 45-50mm to 30-35mm at 4km and from 25-30mm to 20-25mm at 1km. A reduction in peak values was anticipated, but the other significant impact was to shift the area of rain northeast. In the 4km simulation, this had the effect of moving the high totals almost completely away from where they should have occurred and more out over the sea. The shift was less dramatic at

1km. As shown by the schematic Figure 26, the runs with water loading initiated the showers further northeast and then the storms took longer to develop, with the most intense area displaced northeast. This highlights how sensitive forecasts of localised storms can be to changes in model formulation. To predict the storms correctly requires a correct representation of the larger-scale dynamics, the local dynamics and the cloud-scale physics and dynamics. The inclusion of the water loading term is more correct and should be retained, but in this instance it did not give the best results. The challenge is to find out why.

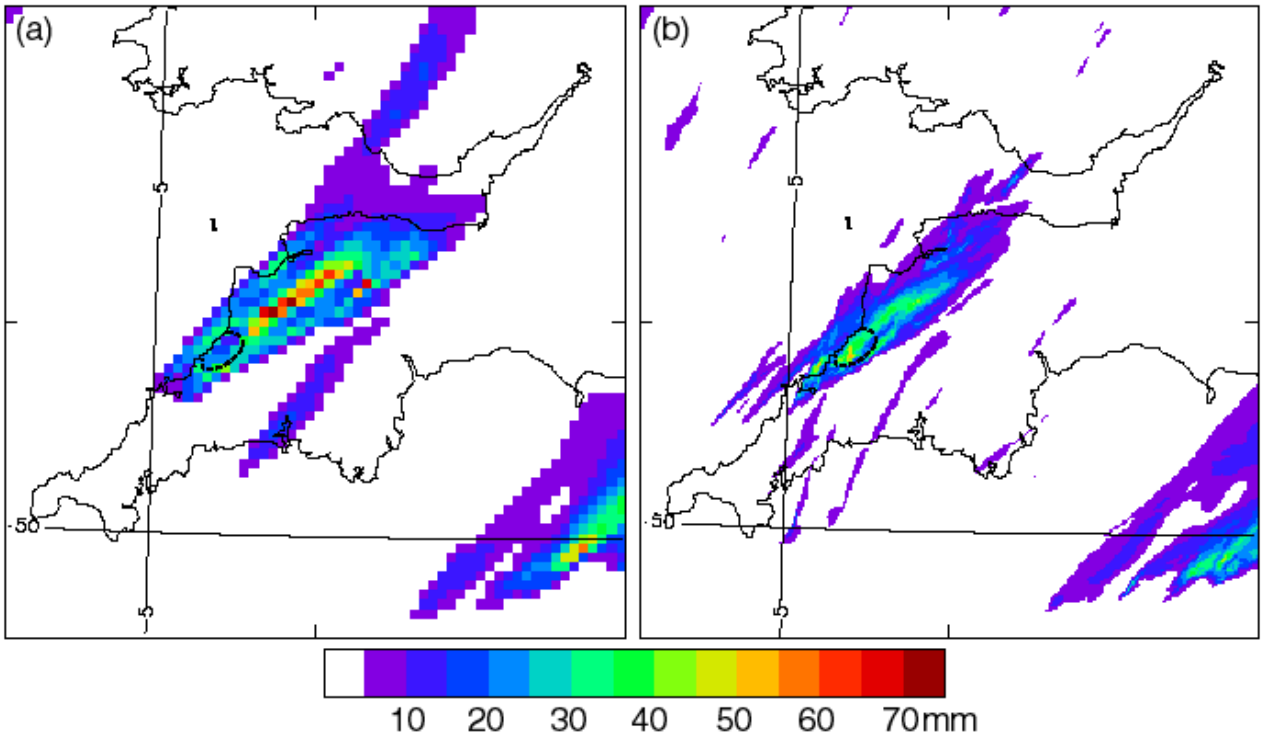

Figure 24. Rainfall accumulations over the period 12 to 18 UTC 16th August 2004 from (a) 4km forecast starting at 01 UTC and (b) 1km forecast starting at 01 UTC. Dashed line encloses accumulations > 50mm from radar (5km resolution), or 100mm from gauges (Figure 20).

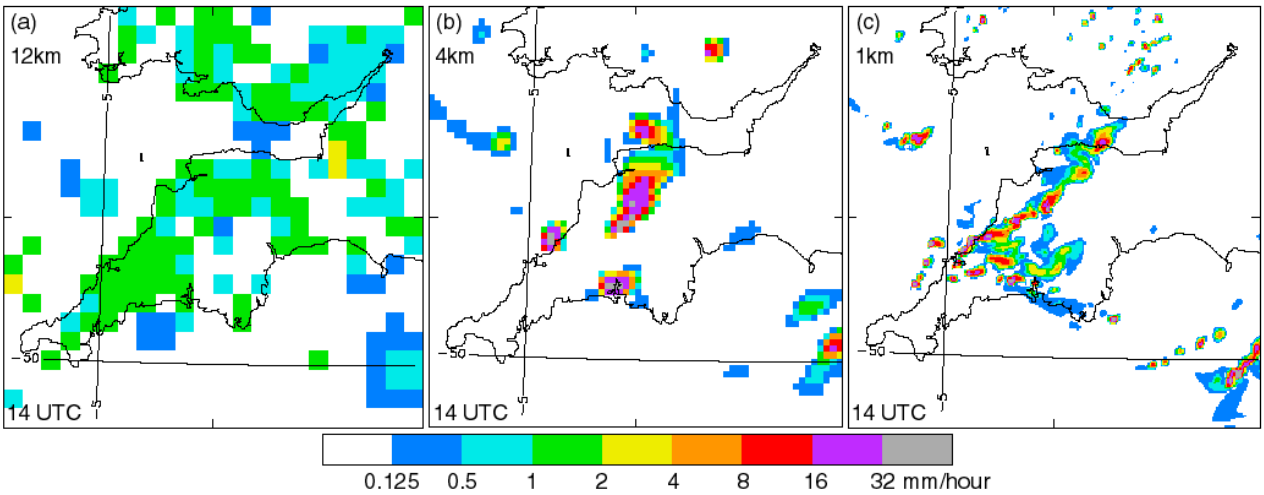

Figure 25. Rainfall rates at 14 UTC 16th August 2004 from (a) 12km forecast starting at 00 UTC, (b) 4km forecast starting at 01 UTC and (c) 1km forecast starting at 01 UTC.

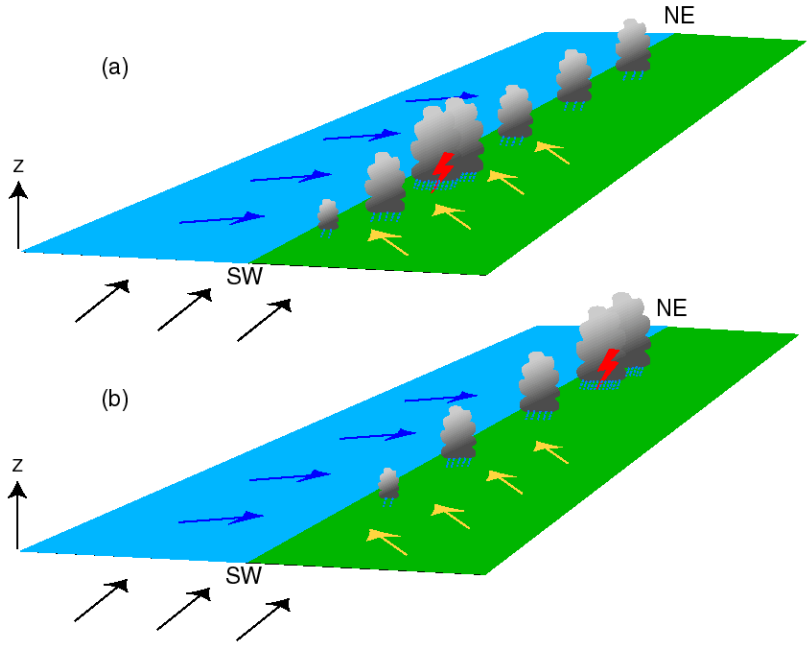

Figure 26. Simple schematic of the distribution of showers and storms along the coast when comparing the behaviour of (a) forecast without water loading (see text) and (b) forecast with water loading.

5 Case 4 7-8th January 2005

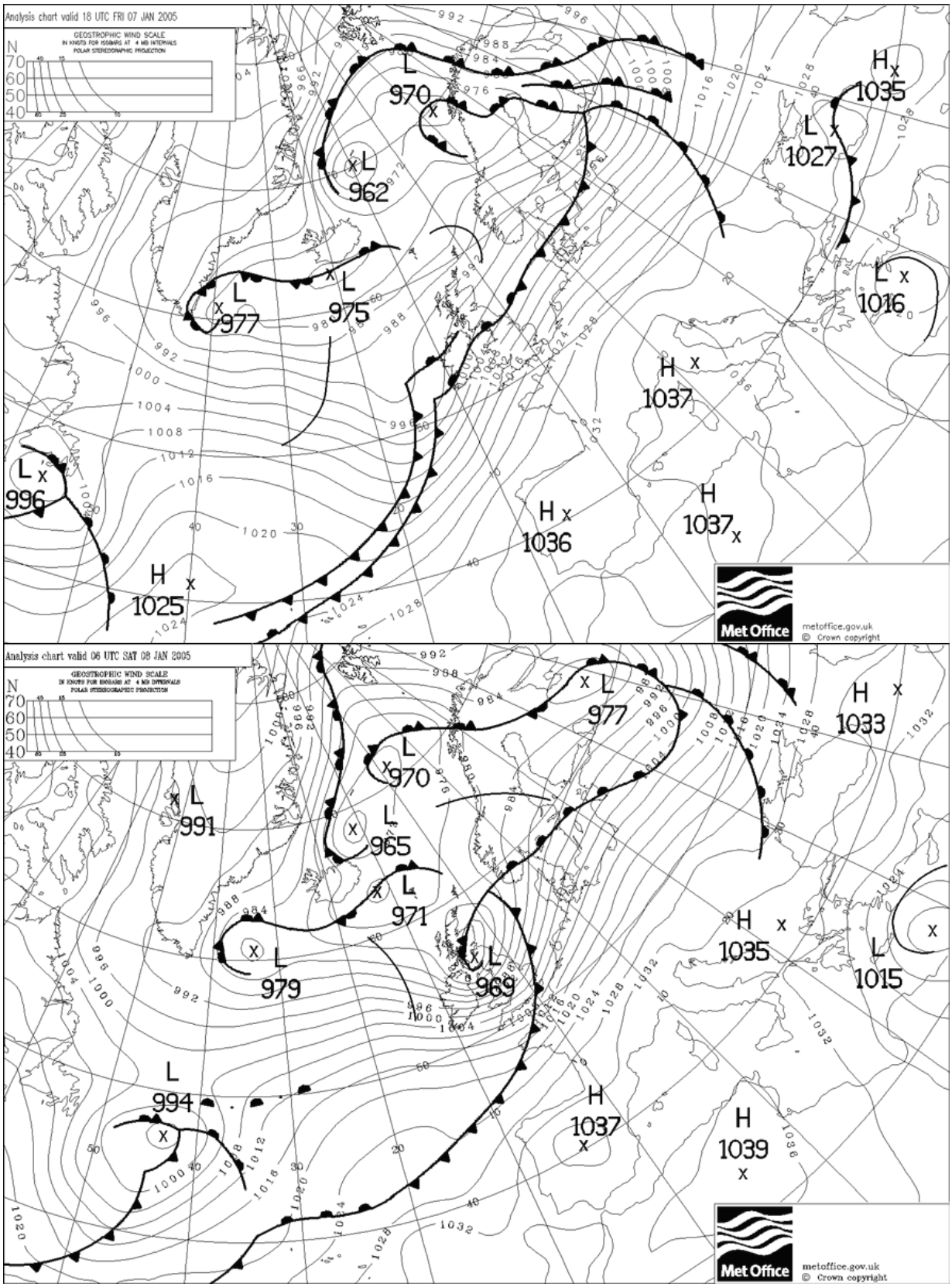

Figure 27. Synoptic charts for 18 UTC 7th January 2005 and 06 UTC 8th January 2005.

5.1 Description of the event

Two successive and very different types of rainfall event led to serious flooding in the city of Carlisle on the 8th January 2005.

Firstly, during the 7th and through into the early hours of the 8th the northwest of England was under the influence of a warm and very moist south-westerly flow. A quasi-stationary waving frontal system brought a period of almost continuous rain to much of Cumbria (Figure 27(a)). Very large quantities of rain were measured over the mountains of the Lake District and the Pennines because of enhancement by the so-called 'seeder-feeder' effect. A schematic of the mechanism is shown in Figure 30(a). The 'feeder' cloud is formed over the hills as warm moist low-level flow is forced to ascend, then as rain from the frontal 'seeder' cloud falls through the 'feeder' cloud it washes out additional droplets to produce a much higher rainfall rate than would have otherwise occurred from the frontal cloud alone. Most of the rainfall came from this period of enhanced orographic precipitation. A schematic of the meteorological situation is depicted in Figure 30(a).

Later, during the morning of the 7th the situation changed and a rapidly developing cyclone brought strong winds and a further short-lived period of rain to the same region. The cumulative effect of all this rain was the flooding in Carlisle later on the 8th.

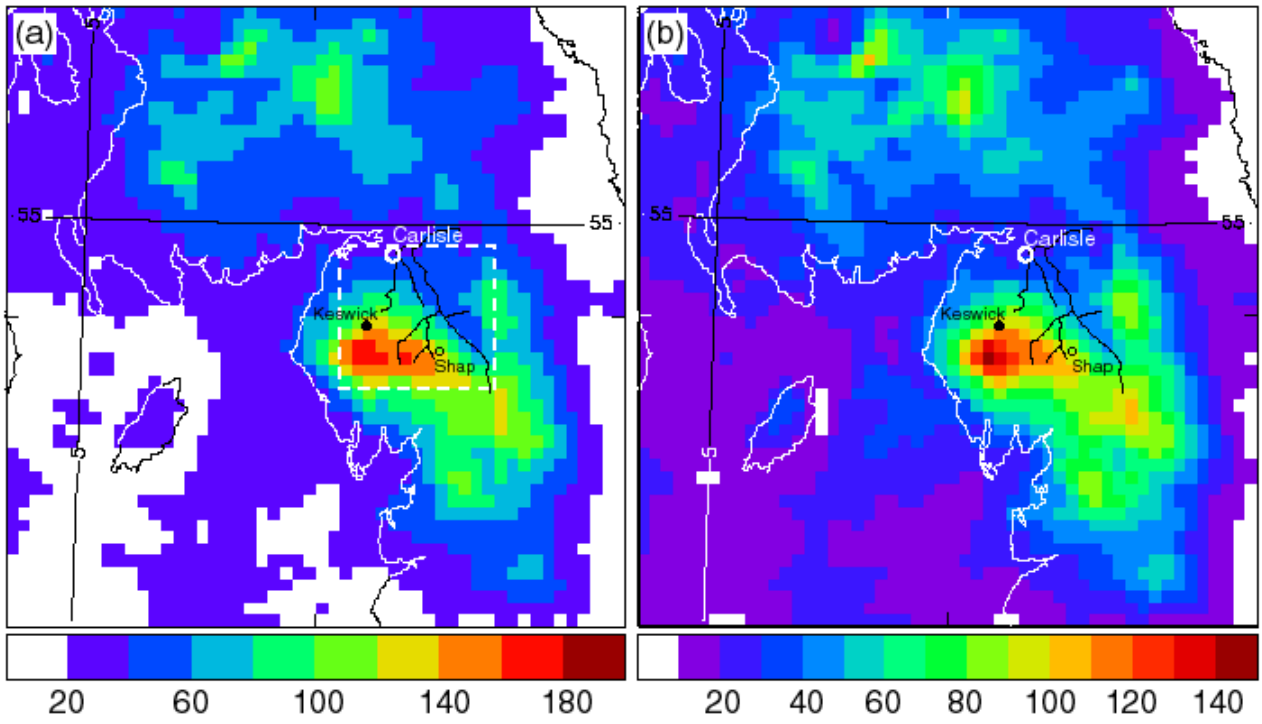

Figure 28. Rainfall accumulations from radar over the period (a) 36 hours 00 UTC 07/01/05 to 12 UTC 08/01/05, (b) 24 hours 09 UTC 07/01/05 to 09 UTC 08/01/05. Towns mentioned in the text are labelled. The black lines show significant rivers that feed into Carlisle. The dashed square in (a) encloses the area used for computing the graph in Figure 29.

Accumulations from radar (Figure 28) show a very clear maximum over the Lake District. In the 36 hours from 00UTC 7th until 12UTC 8th more than 160mm of rain was measured by radar over some 5x5km squares and more than 100mm over a very wide area (~2700km^2). Point measurements from rain gauges over the 24-hour period from 09UTC 7th to 09UTC 8th gave

119.8mm at Shap and 95.0mm at Keswick. Using the FEH method this gives an approximate return period of ~61 years for Shap and ~22 years for Keswick (Information from the National Climate Information Centre (NCIC)). These values can be compared with radar over the same period (Figure 28(b)), which measured around 80-90mm at Shap and around 90-100mm at Keswick. There appears to be an underestimation by the radar of 20-30mm at Shap, which may simply be a sampling issue, but could also be real and will be discussed later. The return periods from the 24-hour gauge measurements were not particularly impressive, and not in the realms of an extreme event (~100 years). However, most of the rain fell on the hills nearby over a longer period, and it is the large spatial extent of very high totals feeding several rivers converging on Carlisle that resulted in the flooding.

As previously mentioned, the rain came from two different meteorological situations. This report will only concentrate on the period of orographically enhanced rain. Since the rain fell over such a long period a smaller time window was required for comparison with an initial run of the 1km model. Conveniently, the highest amounts fell in three distinct periods marked A, B and C in Figure 29. The peaks labelled A and B came within the period of orographic enhancement and C from the cyclone. Period B stands out as being the wettest few hours and was therefore chosen for forecast comparison.

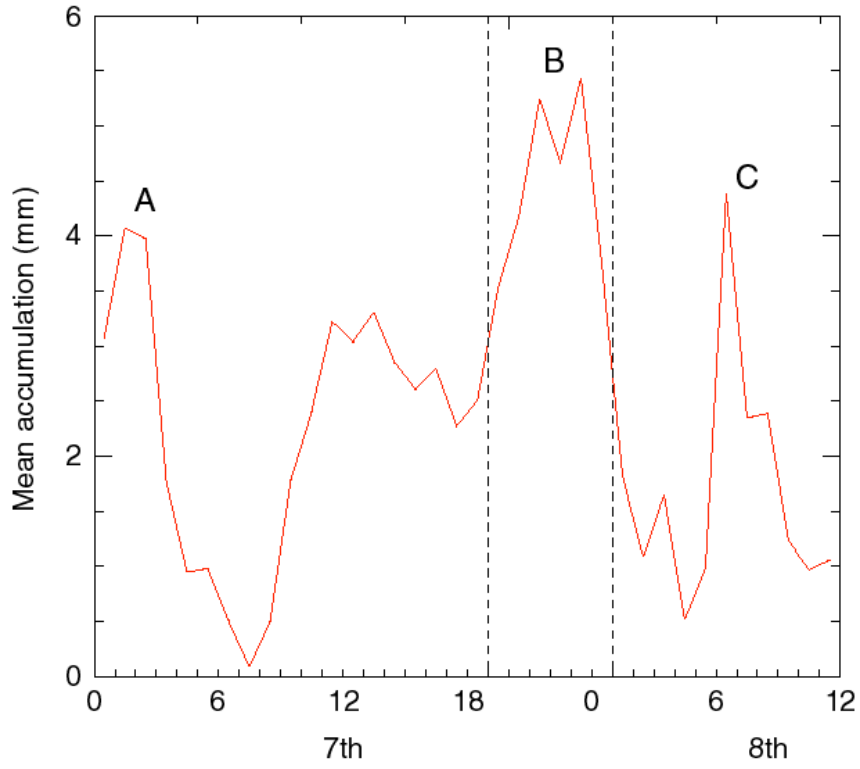

Figure 29. Graph of hourly rainfall accumulation from radar over the period 00 UTC 7th January 2005 to 12 UTC 8th January 2005 within the area enclosed by the dashed line in Figure 28.

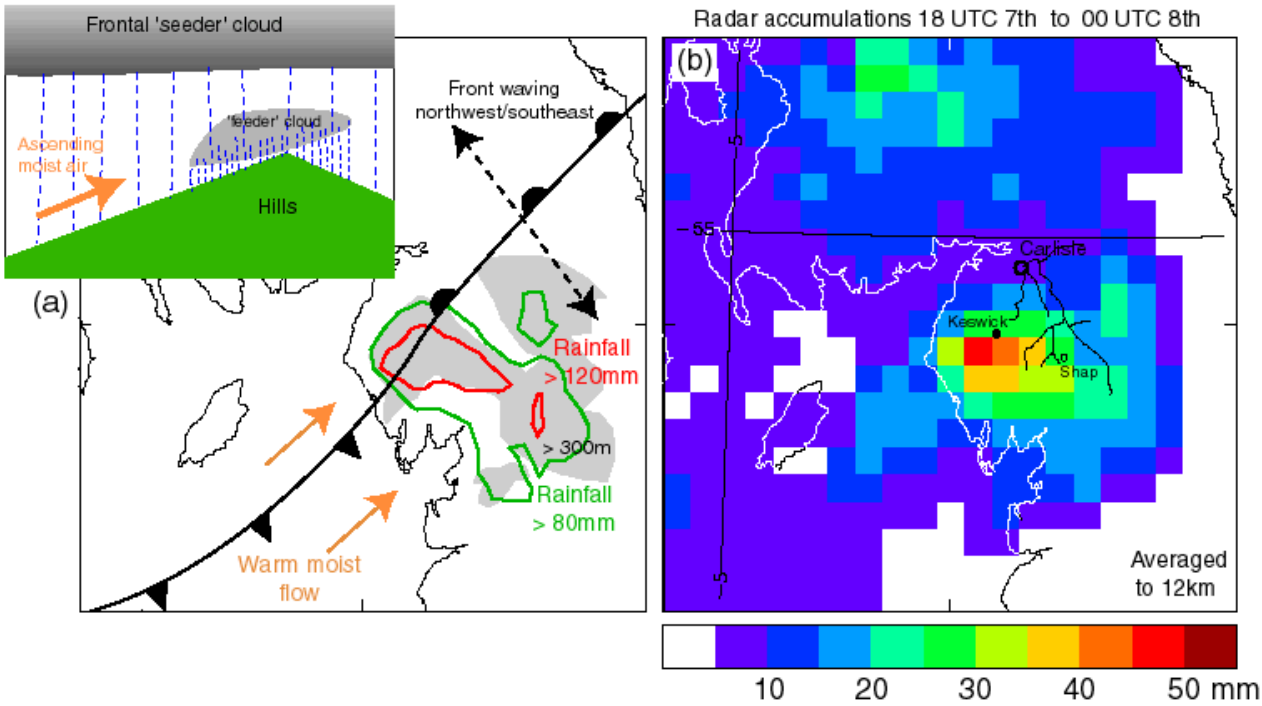

Figure 30. (a) Schematics of the meteorology of the period of orographically enhanced rainfall and the 'seeder feeder' mechanism. (b) Rainfall accumulations from radar over the 6-hour period 18 UTC 07/01/05 to 00 UTC 08/01/05 averaged to the operational mesoscale model 12km grid. The black lines show significant rivers that feed into Carlisle.

5.2 Operational 12km forecasts

Rainfall accumulations from operational 12km model forecasts (Figure 31) can be directly compared with rainfall accumulations over the same period from radar averaged to the same 12km grid (Figure 30(b)). All the operational forecasts were able to produce an enhanced area of rain over the mountains of the Lake District mountains. However, they produced significantly less rain than was measured by radar (~20mm or 40% less over 12x12km squares). In particular, there was not enough rain over the important river catchments. Another characteristic was a tendency to produce too much rain along the west coast. It is noticeable that all the forecasts look similar except for a trend towards more rain to the north of Carlisle in the later forecasts. This is an indication that the meteorological situation was reasonably predictable up to a day ahead; more so than is usually the case with convective events. The important factors were the quantity of rain and local detail in the spatial distribution.

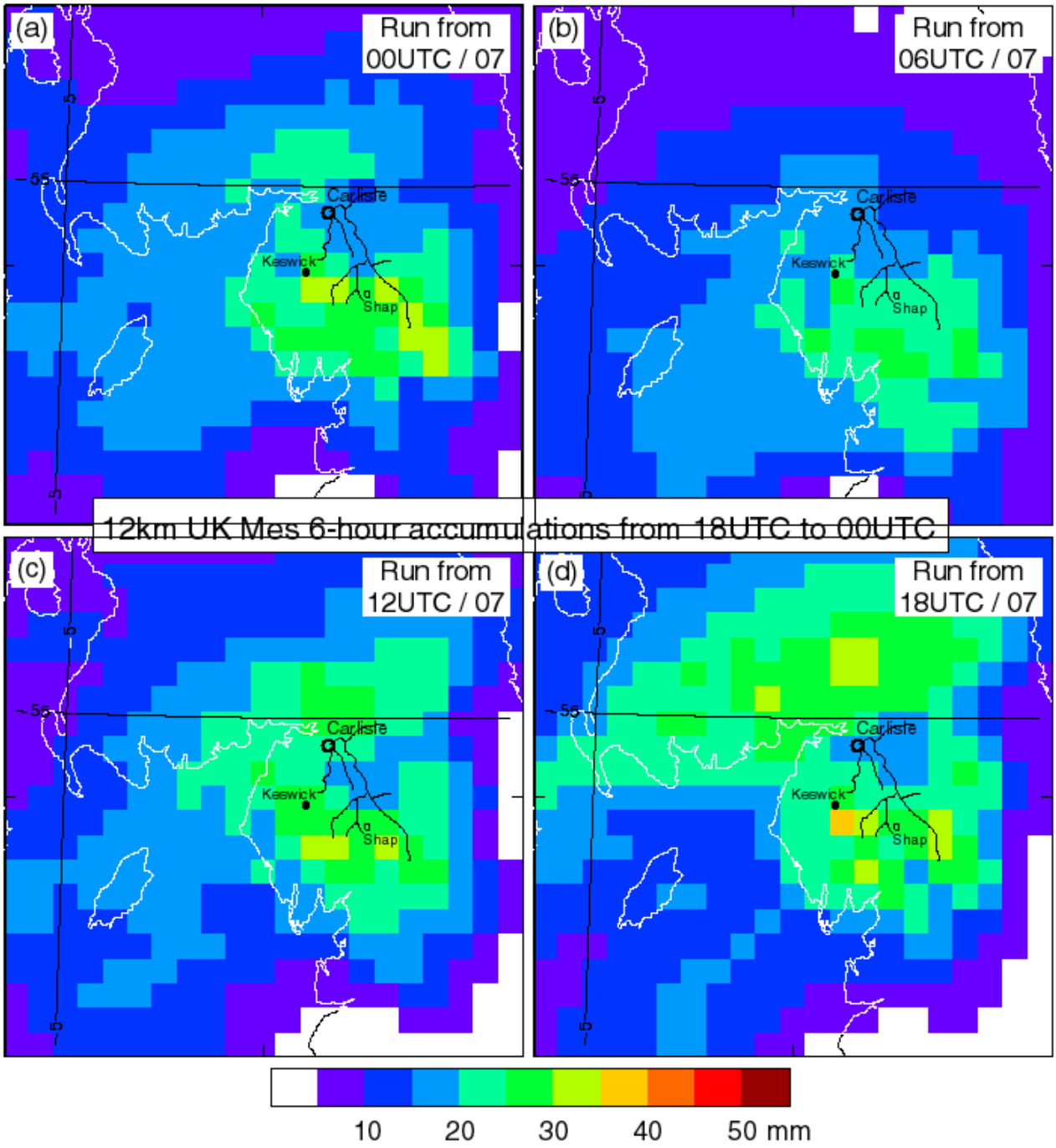

Figure 31. Operational mesoscale model forecasts of rainfall accumulations over the 6-hour period 18 UTC 07/01/05 to 00 UTC 08/01/05. Forecasts started from 00, 06, 12 and 18 UTC 07/01/05. The black lines show significant rivers that feed into Carlisle.

5.3 The high resolution forecasts

The model was run with a grid spacing of 4km and 1km from 19 UTC on the 7th using data at 19 UTC from the 18 UTC 12km forecast as the starting point. Accumulations averaged to 12km for the 5-hour period from 19 UTC to 00 UTC are shown in Figure 32. (A 6-hour period from 18 UTC can not be examined because 18UTC precedes the start of the 1km and 4km forecasts).

There were notable differences between the high resolution simulations and the 12km forecasts in terms of quantity of rain and spatial distribution. Both the 4km and 1km forecasts produced considerably more rain than any of the operational forecasts. The peak values (40-50mm) were much more in line with those observed by radar; perhaps a little more given the shorter accumulation period. The other characteristic of the high resolution simulations was that the highest rainfall was more concentrated over the highest part of the mountains; whereas the 12km forecasts spread the rain out more widely. In this regard, the 4 and 1km simulations once again compare more favourably with radar.

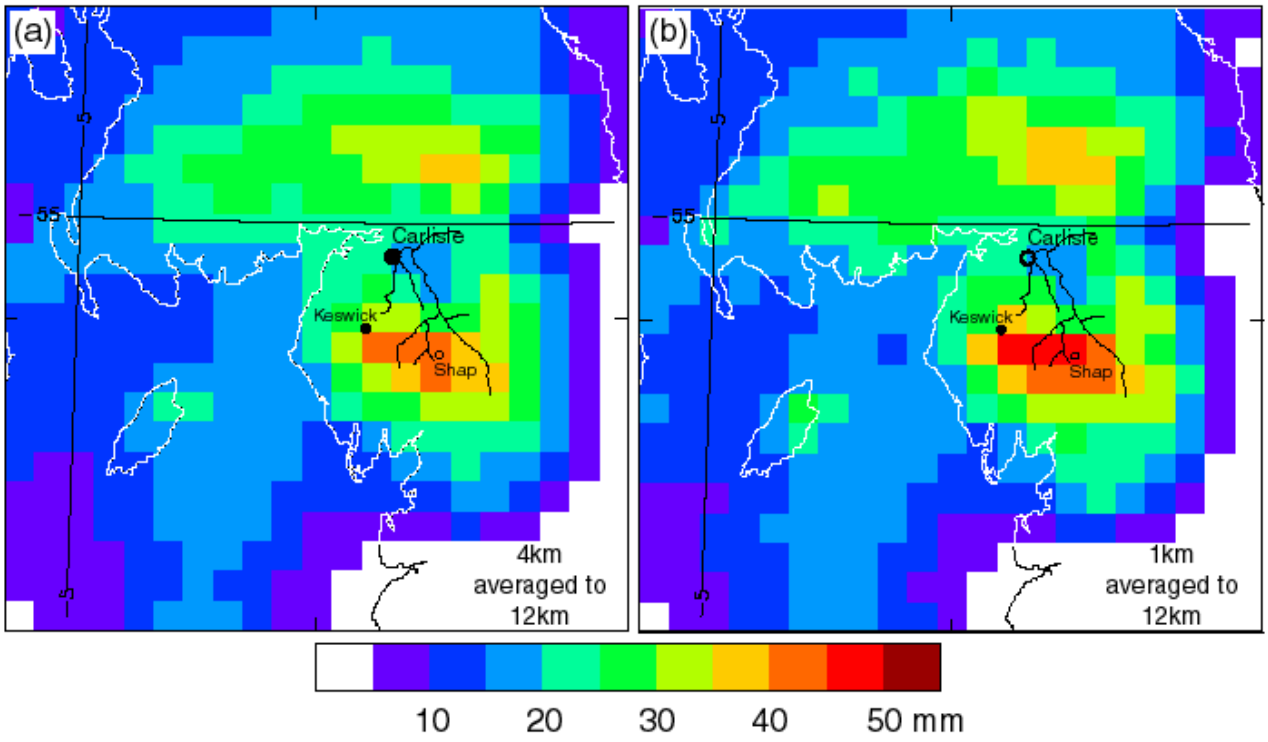

Figure 32. Forecasts starting from 19 UTC 07/01/05 of rainfall accumulations over the period 19 UTC 07/01/05 to 00 UTC 08/01/05 averaged to the mesoscale model 12km grid from (a) 4km model (b) 1km model. The black lines show significant rivers that feed into Carlisle.

When compared with each other (see Figure 33), the clear difference between the 4km and 1km forecasts was that the largest totals (over the mountains) in the 1km model were higher by around 5-10mm than the equivalent in the 4km forecast. Elsewhere the accumulations were very similar and the spatial distribution of the rainfall was almost identical.

The message up to this point has been one of success for the high-resolution forecasts. However, there is an important difference between those forecasts and the radar that has not yet been discussed and requires some comment. Both the high-resolution models generated high totals further to the east and southeast than observed by radar. A comparison of the 12km

averaged radar accumulations in Figure 30(b) and the 1km accumulations averaged to 12km in Figure 32(b) shows that the highest 1km forecast accumulations extended from south of Keswick eastwards beyond Shap, whereas the highest radar totals were mainly restricted to an area south of Keswick. The significance is that the 1km forecast appears to have predicted too much rain over the important river catchments that fed the rivers flowing into Carlisle. The comparison is only over a period of a few hours, but given that the same conditions persisted for more than a day it is likely that a 24-hour forecast at 1km would have produced the same signal. The evidence suggests that the 1km forecast was wrong where it counts most, but we need to question the evidence.

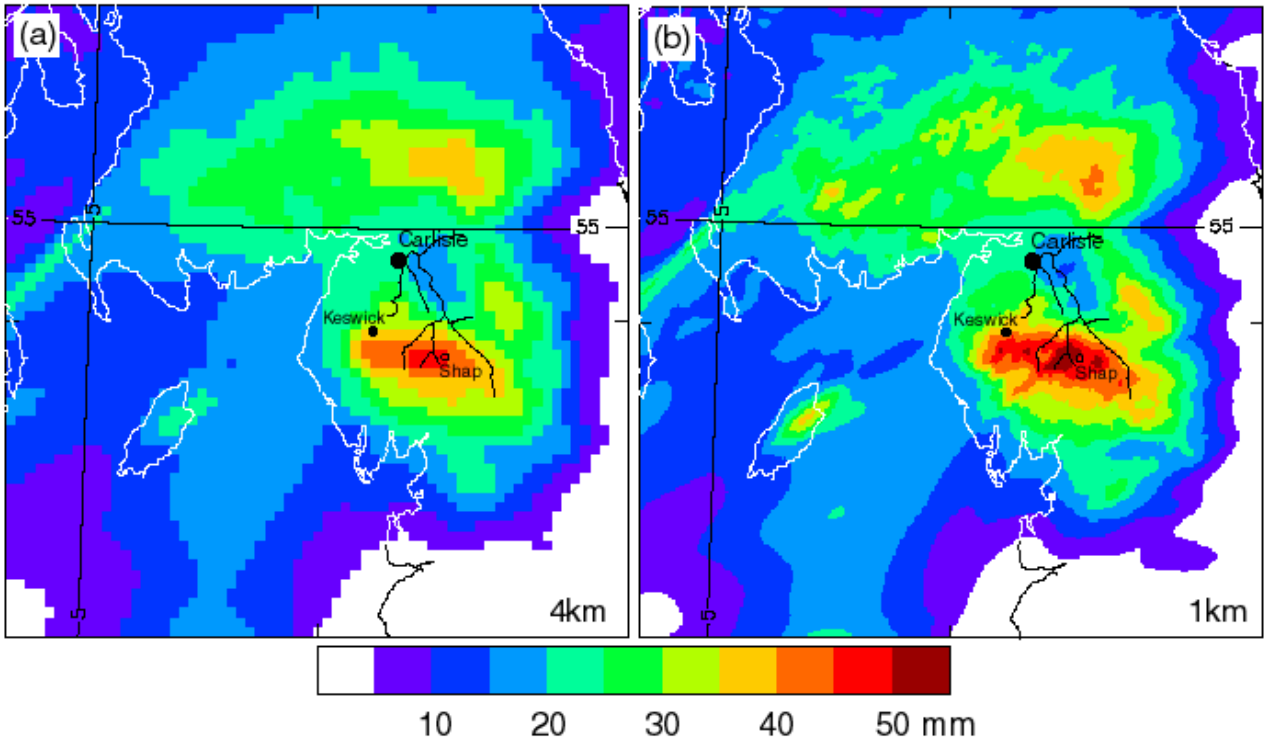

Figure 33. Forecasts starting from 19 UTC 07/01/05 of rainfall accumulations over the period 19 UTC 07/01/05 to 00 UTC 08/01/05 from (a) 4km model (b) 1km model. The black lines show significant rivers that feed into Carlisle.

Nimrod radar data is post-processed to take account of the inability of radar to detect rainfall enhancement from the seeder-feeder mechanism. The way this is done is to use fields from the operational 12km forecasts to enhance the rainfall totals where appropriate. It is thought that in general this produces more realistic totals over mountainous areas, but it does mean that the radar rainfall we are verifying against is not a pure observation; it comes partly from a numerical model. The enhancement depends on the wind and relative humidity (RH) at 850 metres (moister air = more enhancement if RH>85%). The RH is modulated by ascent and descent and therefore the flow over the 12km model orography (ascent = increasing RH), which is coarse and at a relatively low altitude over the Shap area (Figure 34). So even though the enhancement is applied using high resolution Nimrod orography, it is not surprising that the radar accumulations have a resemblance to the 12km orography. In addition, the orographic enhancement does not take into account rain drifting horizontally as it falls and therefore rain falling on the lee side of hills. These are possible reasons why the radar observed 20-30mm less rain at Shap than was measured by rain gauge. The implication is that since the 1km model has an accurate representation of the orography and can model wind drift, it may well have given a more accurate prediction of the rainfall than the radar data used to verify it. It produced

considerably more rain over the river catchments of interest, which is certainly reasonable given the eventual magnitude of the flooding in Carlisle. The tentative conclusion is that the 1km forecast was more accurate than even the radar measurements, but clearly we have to be cautious when verification is so difficult.

Another way to verify the forecasts that does not rely on radar is to feed the output into a hydrological river flow model. This was done at the Joint Centre for Hydro-Meteorological Research (JCHMR) (personal communication) for this case using the River Flow Model (RFM) developed at the JCHMR to compare with flow measurements from a river gauging station. They used Nimrod radar data as the input; it would be interesting to see how the NWP forecasts compared.

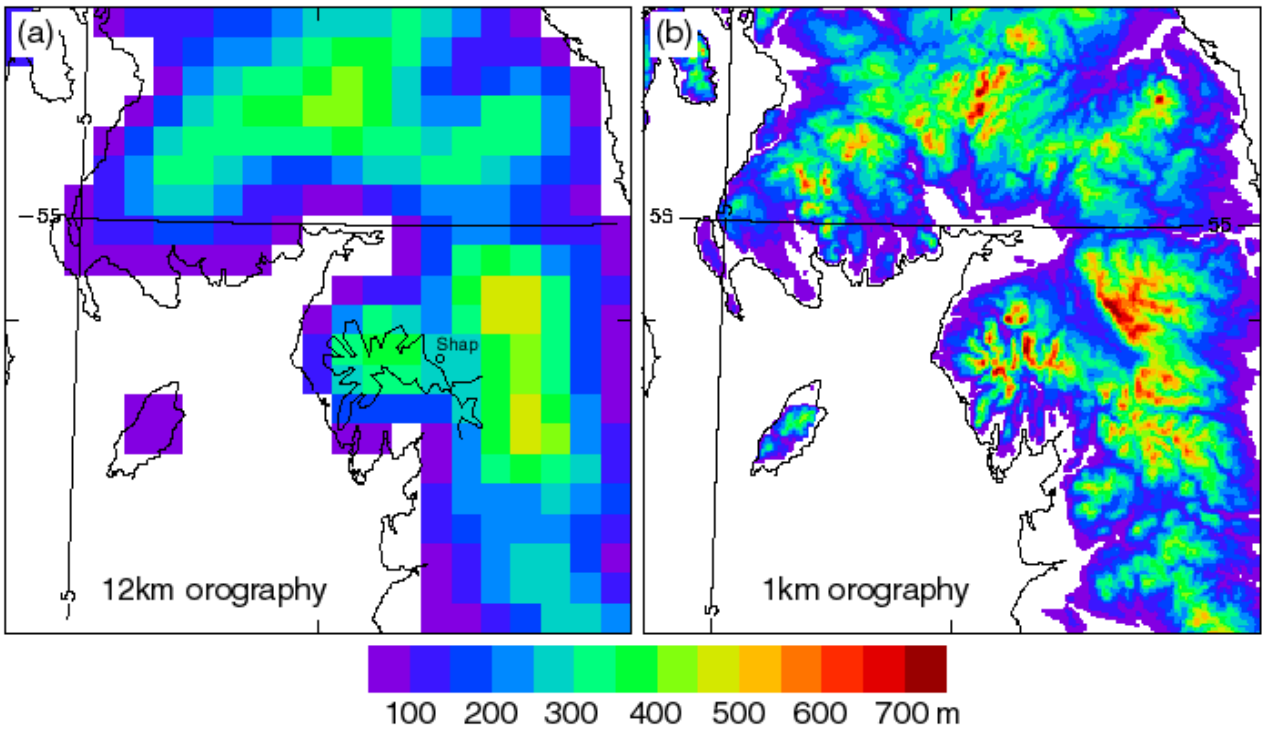

Figure 34. Model orography for (a) operational 12km mesoscale model and (b) 1km grid-length model. The black line in (a) gives a rough guide to a 300m contour in (b).

6 Case 5 19th June 2005

6.1 Description of the event

On the 19th June 2005 most of the UK was under the influence of hot humid air that had been advected northwards from the continent. The synoptic chart for 12 UTC is shown in Figure 35.

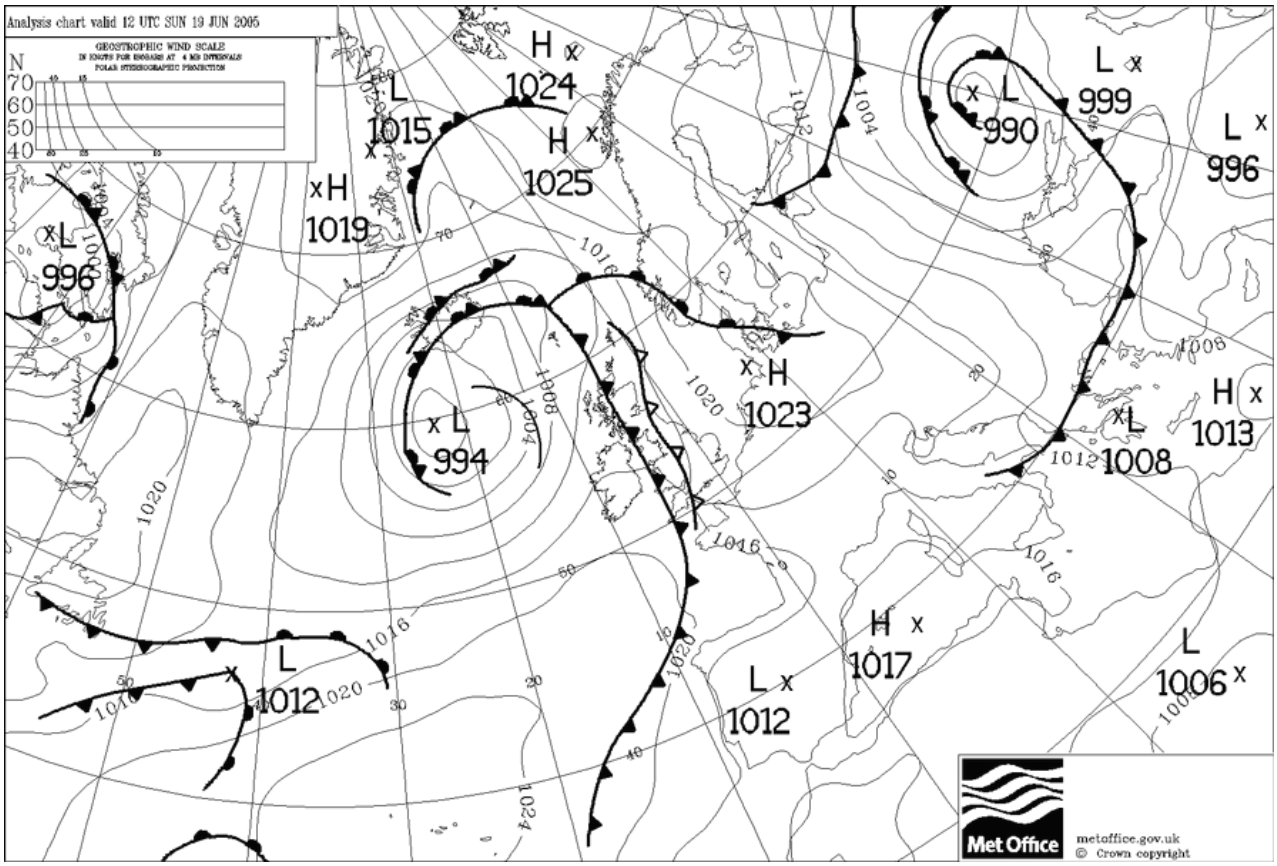

Figure 35. Synoptic chart for 12 UTC 19th June 2005.

A cold front over western areas marked the boundary between the hot air and cooler air from the Atlantic. Thunderstorms developed during the afternoon along the line marked as an upper-cold-front (line with open triangles) on the synoptic chart. It is debatable whether this really was an upper-cold front or just a means of depicting the line along which convection developed ahead of the cold front. Satellite water-vapour imagery (not shown) reveals that an area of dry air at upper levels had its leading edge much further east than the analysed upper front. Evidence from mesoscale model output suggests that there may have been a convergence line near the surface where the upper front was analysed. This is shown schematically in Figure 38. The region where the atmosphere was unstable to deep convection lay between the cold front to the west and the upper-level humidity front to the east. Within that zone, convection developed preferentially along a wavy line from the West Midlands to North Yorkshire (again see Figure 38). The most intense rainfall was concentrated in a small region to the northwest of the village of Hawnby. Figure 36(a) shows rainfall totals in excess of 90mm in the 6-hour period from 12 to 18 UTC; with most of that rain falling between 16 and 17 UTC. At Hawnby itself the radar measured around 70mm. The rain gauge at Hawnby (information provided by the

Environment Agency) recorded 69.4mm in three hours, of which 59.8mm fell in one hour and 50.6mm in just half an hour. All these totals have a return period of more than 200 years (using the Flood Estimation Handbook method). The result of all that rain was flash flooding at Hawnby, the larger village of Helmsley and the surrounding area. Several people were rescued by helicopter, houses were flooded and bridges destroyed.

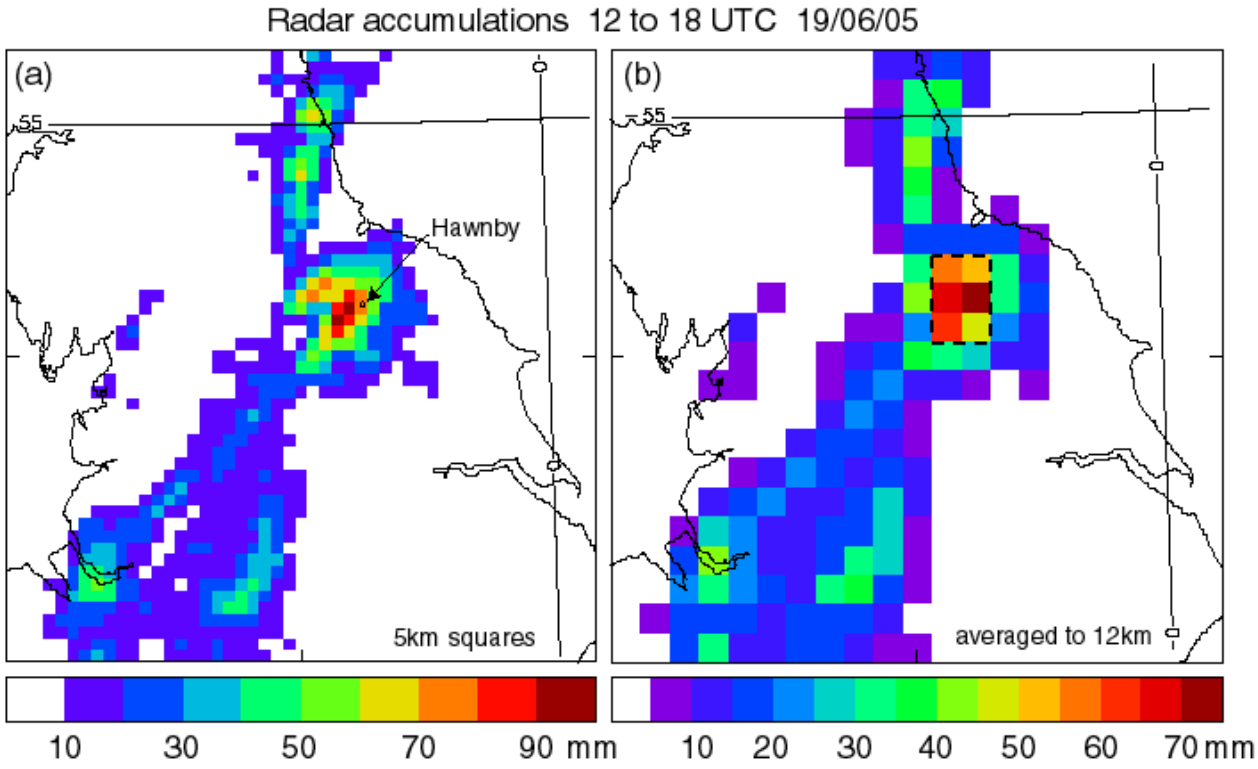

Figure 36. Rainfall accumulations from radar over the period 12 to 18 UTC 19th June 2005, (a) on 5km grid and (b) averaged to operational mesoscale model 12km grid. Dashed line in (b) encloses accumulations >45mm.

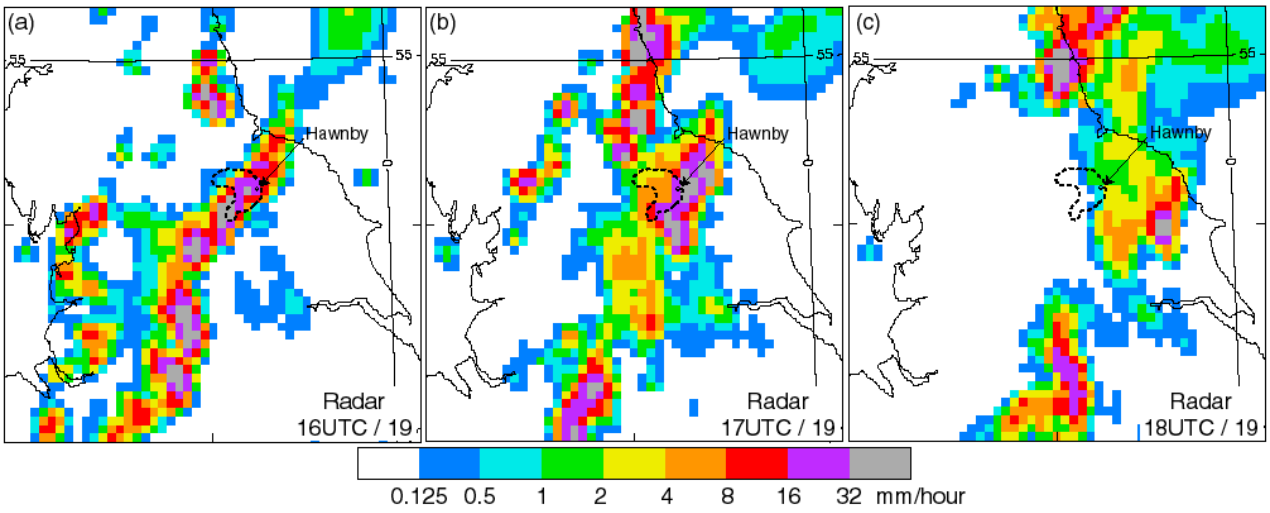

Figure 37. Rainfall rates (mm/hour) from radar at 16, 17 and 18 UTC 19th June 2005.

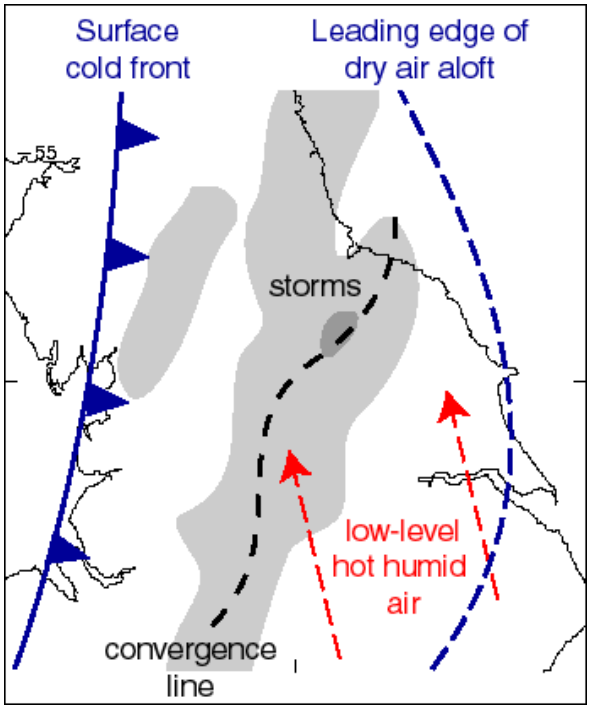

Figure 38. Schematic of the main meteorological features associated with thunderstorms during the afternoon of 19th June 2005.

6.2 Operational mesoscale 12km model forecasts.

Rainfall accumulations over the period 12 to 18 UTC 19/06/05 from four operational mesoscale model forecasts are shown in Figure 39. The pictures can be directly compared with radar accumulations over the same period and on the same grid (Figure 36(b)). Clearly, none of the forecasts managed to predict the high rainfall totals although they did all produce some convective rain. The forecast that started at 00 UTC did the best by generating totals over 25mm, but that is not even close to the 70mm observed by radar on the same grid, and the highest totals were wrongly positioned by more than 50km. Curiously, the worst forecast started at 12UTC (closest to the event); it produced very little rain generally and none of any significance. It is not unexpected that the 12km model struggled with this type of convective situation. It has to rely on a convection parametrization scheme to represent showers that can not be resolved. However, the storms in this instance were not as small and localised as in some of the other cases. They were ~30-50km across in a band stretching more than 100km over a period of a few hours, so there might be good reason to think the model should have done better.

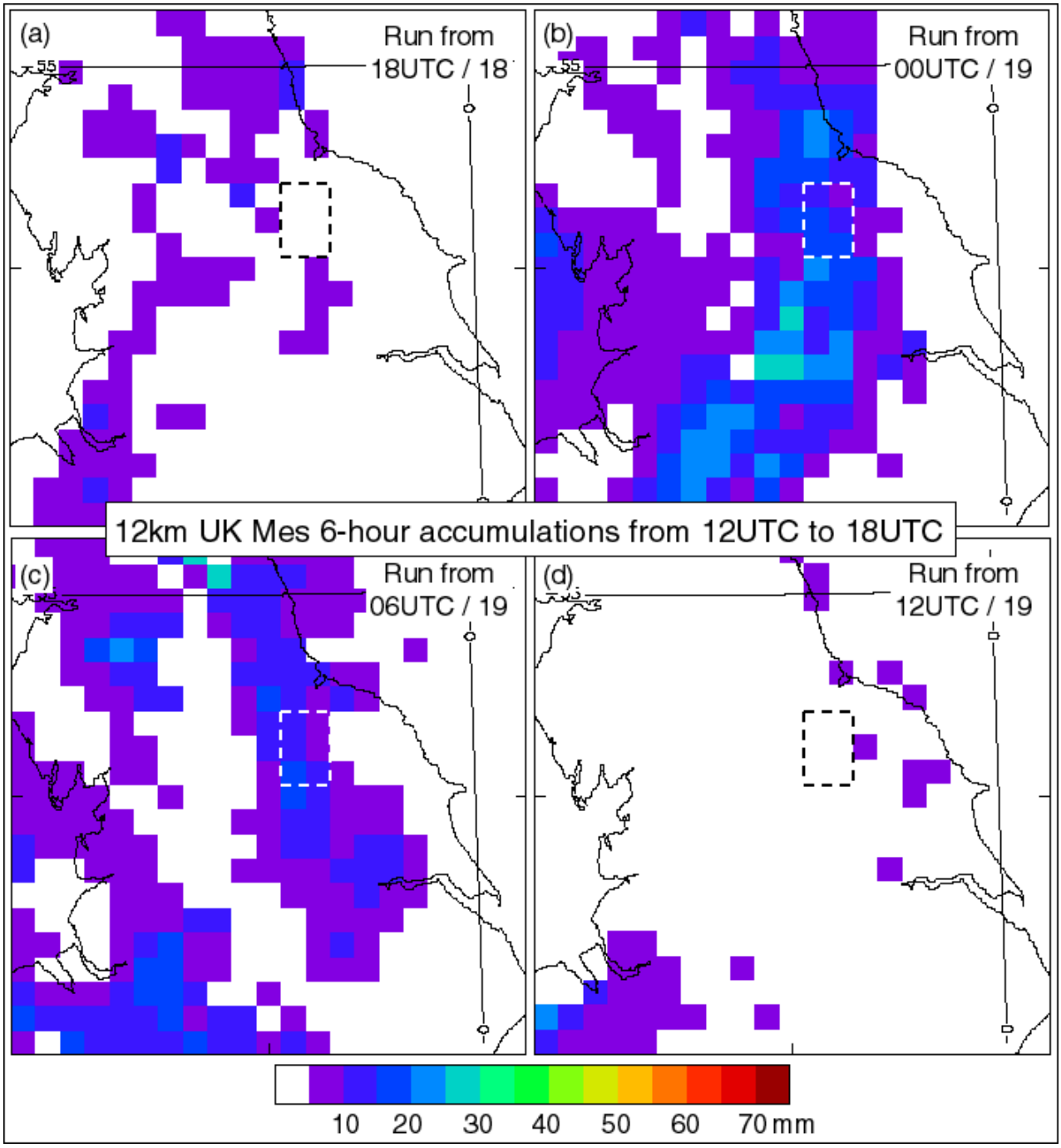

Figure 39. Operational mesoscale model forecasts of rainfall accumulations over the 6-hour period 12 to 18 UTC 19/06/05. Forecasts started from 18 UTC 18/06/05 and 00, 06, 12 UTC 19/06/05. Dashed line encloses accumulations > 45mm from radar (Figure 36(b)).

6.3 High resolution model forecasts

Forecasts were run at 4km and 1km from 07 and 13UTC. Rainfall accumulations over the period 12 to 18 UTC (13 to 18 UTC from the 13 UTC run) averaged to the 12km grid are displayed in Figure 40.

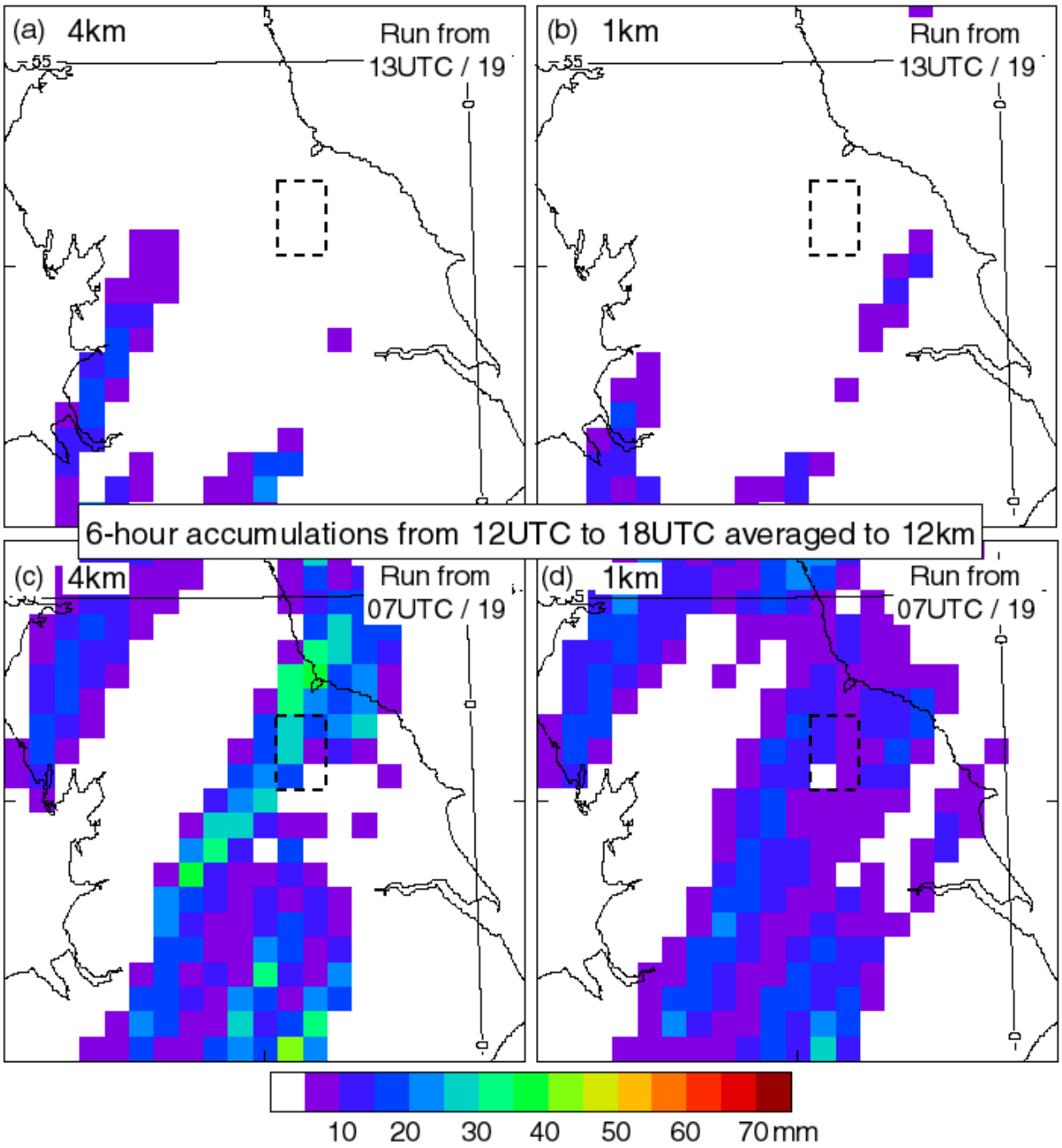

Figure 40. Rainfall accumulations over the period 12 to 18 UTC 19/06/05 averaged to the operational mesoscale model 12km grid - (a) 4km forecast from 13 UTC, (b) 1km forecast from 13 UTC, (c) 4km forecast from 07 UTC and (d) 1km forecast from 07 UTC. Dashed line encloses accumulations > 45mm from radar (Figure 36(b)).

At face value the high-resolution forecasts from 07 UTC gave a very slight improvement compared to 12km, whilst the forecasts from 13 UTC were worse. Taking the 07 UTC forecasts to begin with; the 4km simulation was able to generate 12km-averaged accumulations of more than 35mm within 30km of the target area, the 1km model could not manage more than 20mm. It can be seen from Figure 41 that the 4km forecast without any averaging produced peak accumulations of over 65mm, though with a displacement error of ~40km to the north. The 1km forecast failed to generate more than 25-30mm anywhere within 50km of Hawnby. Both forecasts were able to simulate a southwest-northeast rainfall pattern in line with the movement of the storms; something that the 12km forecasts were unable to produce because individual storms were unresolved.

The 4km forecast from 07 UTC was successful in predicting a threat of flood-producing rainfall somewhere in North Yorkshire during the afternoon, but specific locations were wrong. In contrast, the 1km forecast did not produce sufficient rain to give a serious indication of a flood threat. Why the difference? Two reasons can be given. Firstly, the 1km forecast initiated showers too early and over too wide an area. This speckling of smaller storms was never focussed into a single band so that heavy rain could not persist over the same location for long enough, even though the rainfall intensities were high over small areas (Figure 43). The swath of rain (shown in Figure 41) for the 1km forecast was very wide. Where the cells were more concentrated in the north of the domain, accumulations exceeding 65mm were produced. Secondly, the 4km model has a tendency to generate storms that are sometimes unrealistically large and intense. Some of these storms could produce large quantities of rain simply because of their size, in which case there may also be several false alarms where too much rain is predicted, as indeed occurred (compare Figure 41 with Figure 36).

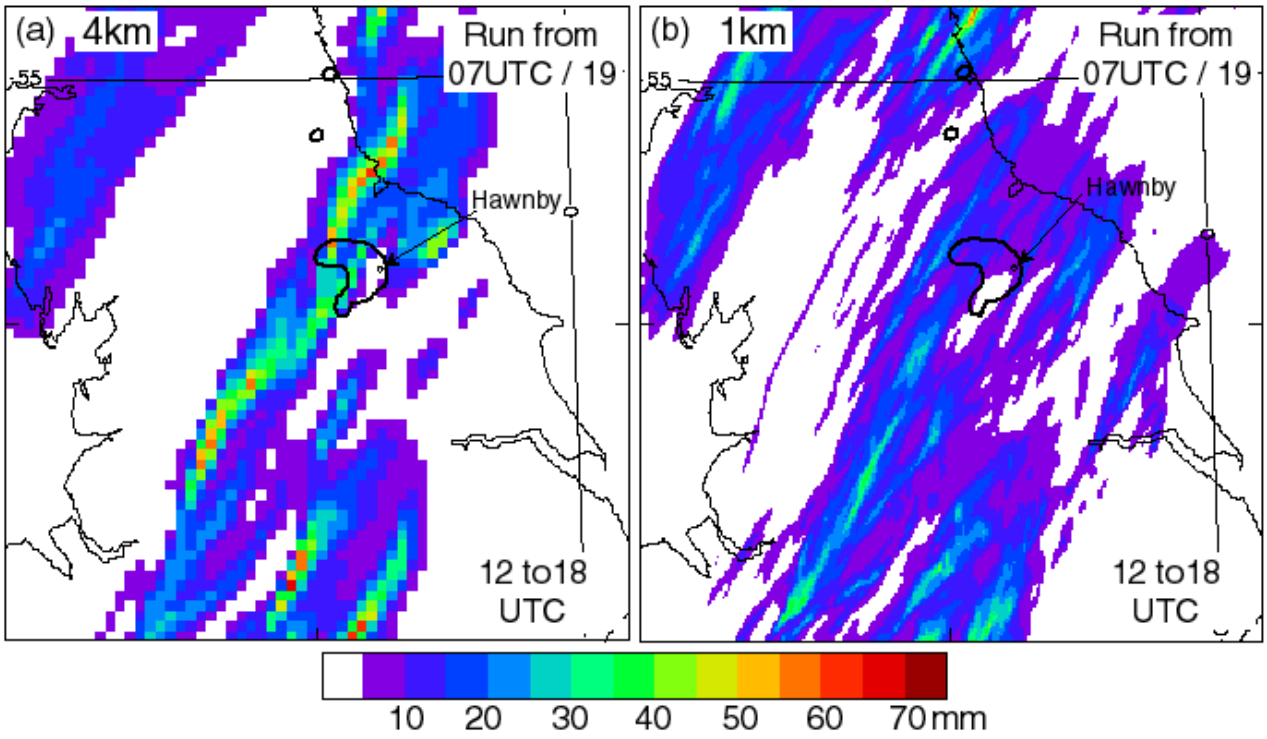

Figure 41. Rainfall accumulations over the period 12 to 18 UTC 19th June 2005 from (a) 4km (b) 1km forecast starting at 07 UTC. Black line enclose accumulations > 60mm from radar (Figure 36(a)).

Moving on to the forecasts from 13 UTC (Figure 40(c & d)). Both the high resolution forecasts were very poor even though the time between the start of the forecasts and the development of the main storm was only around three hours. They produced no rain over the area of interest, although the 1km model did generate more than 30mm in a narrow band some 40km to the southeast (Figure 42). It is the short forecast time that was partly to blame. Both the 4km and 1km simulations used data from the 12km model at the start and therefore needed time to 'spin up' the model fields to the higher resolution. The result is often a delay in the initiation of convection over the first few hours. It is the reason why it is not appropriate to use high-resolution NWP for very short range forecasts of convection if spinning up from a coarser resolution model.

The 13 UTC forecasts were included in this report to demonstrate the impact of the spin-up period. However, it may not be the only reason for the poor performance. The forecasts were initialised with fields from the 12km forecast starting at 12 UTC. That particular 12km forecast produced very little rain, and it may be that the spin up problem was compounded by a model state that was less prone to triggering storms in the first place.

The 12km forecast that produced the most rain was the one that started from 00 UTC, so it may be interesting to see how much rain is produced by 4km and 1km forecast starting from 01 UTC.

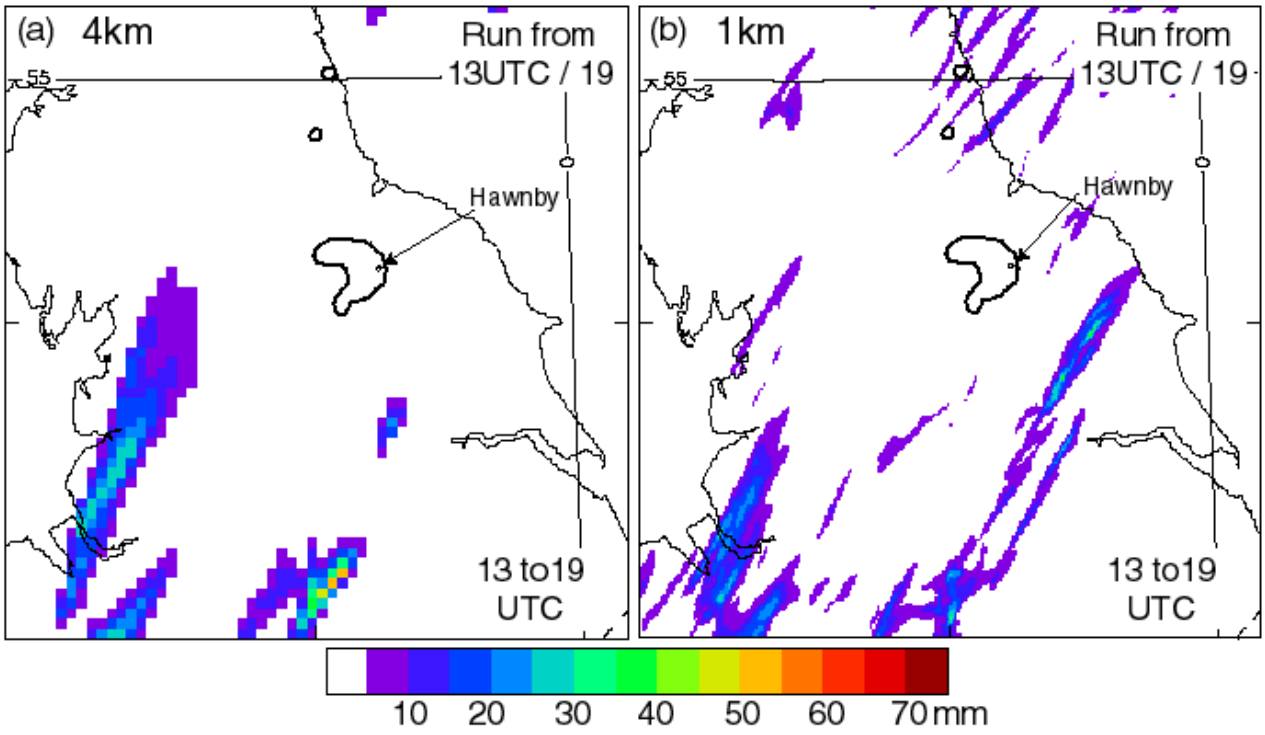

Figure 42. Rainfall accumulations over the period 12 to 18 UTC 19th June 2005 from (a) 4km (b) 1km forecast starting at 13 UTC. Black line enclose accumulations > 60mm from radar (Figure 36(a)).

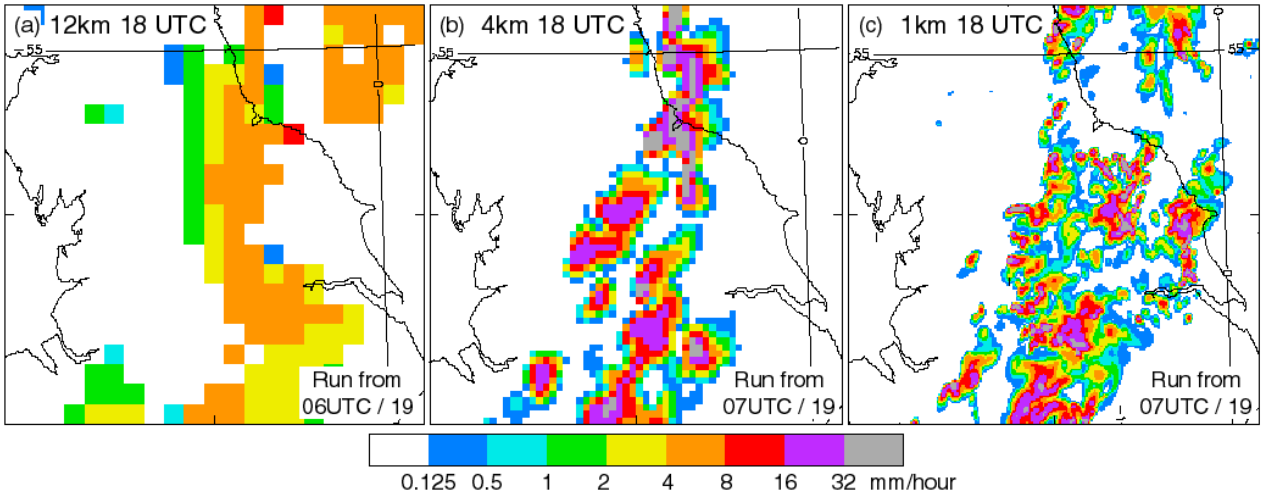

Figure 43. Rainfall rates at 18 UTC from (a) operational 12km forecast starting at 06 UTC, (b) 4km forecast starting at 07 UTC and (c) 1km forecast starting at 07 UTC.

This case represents a serious challenge for high-resolution NWP because of the multi-scale nature of the underlying dynamics and the extreme nature of the event. A large region of instability is focussed down to a more favoured band and focussed down further to the localised extreme rainfall. It is possible that forecasts using the 1km model would be very sensitive to small changes in initial conditions or model parameters as well as to changes in initial conditions on a larger scale – but that needs to be determined.

7 Conclusions

Five cases of extreme rainfall have been documented with along with results from the operational NWP mesoscale model forecasts (12km grid spacing) and NWP model simulations using a grid spacing of 4km and 1km. Four of the cases involved heavy rainfall from intense thunderstorms. One of the cases involved orographic enhancement of rainfall over a prolonged period. The findings from the convective events will be discussed first, then the orographic event, before a brief discussion of where to go next.

7.1 Results from the convective events (thunderstorms).

The challenge to NWP models when predicting this type of event is firstly that they need to capture correctly the multi-scale nature of the environment in which a storm forms and secondly they need to include the specific factors that make the rainfall fall into the category of being extreme. This means getting the larger-scale dynamics, the local dynamics and the cloud-scale dynamics/thermodynamics all correct.

Four elements of forecast skill are critical for a successful forecast:

1. Producing the correct rainfall totals
2. Producing the rain in the correct location
3. Producing the rain at the correct time
4. Producing the rain over the correct area (extensiveness)

Skill criterion 1 – producing the correct rainfall totals.

A ‘storm-resolving’ model (grid spacing ~1km) should be able to perform much better than a model with a grid spacing of 12km because the individual storms can be properly resolved rather than represented by a convection parametrization scheme. Very high rainfall rates are usually localised and could therefore only be represented properly on a fine grid.

Results from the four cases show that the operational 12km model was largely incapable of reproducing the high rainfall totals that were observed. Even when the radar data was averaged to the 12km grid, which is a more realistic comparison for the model, the forecasts failed to deliver on many occasions.

In contrast, the high-resolution forecasts were able to produce high-enough rainfall amounts on most occasions. The 4km model tended to produce the highest totals and was close to the peak values in all four cases. The problem was that it had a tendency to give high totals in too many locations, leading to false alarms and the storms sometimes looked unphysical. The 1km forecasts were also able to produce the high totals correctly for two of the cases (Wittering and London), but under predicted the other two (Boscastle and Hawnby), although still generating much more than the 12km model.

Skill criterion 2 – producing the rain in the correct location.

Determining whether the rainfall was predicted in the correct location really means asking if it fell into drainage area responsible for the flood. This may be a river catchment or a much more localised area if urban.

A high resolution model should be able to do better than a coarser resolution model if it inherits the correct larger-scale dynamics. Then it is the local effects that dominate and these are better resolved.

The operational 12km forecasts were rarely able to produce the higher rainfall totals in the correct location. In general, they produced too little rain over too wide an area. When significant totals were predicted, the position was usually wrong by more than 50km. The exception is one of the forecasts for the London flood case, which had a spatial error of ~10-20km.

The high resolution forecasts did better for some cases and not for others. The showers in the Wittering case were displaced to the east by around 40km at all resolutions. The highest totals were misplaced by at least 40km for the Hawnby event. The reason may be due to an error in the larger-scale dynamics. In contrast, the 1km model in particular produced high totals within the correct catchment area for the Boscastle event and to within 5-15km for the London case. The reason is probably due to more local dynamics playing a greater part.

Skill criterion 3 – Producing the rain at the correct time

Whether the rainfall arrives at the correct time will depend on capturing the timing of the large-scale and local dynamical forcing and then getting the life cycle of the showers correct. This is a difficult challenge for any model. It is made easier if we are more interested in accumulations over a period and then the exact timings of individual storms are not so crucial.

High-resolution models will be better at modelling the life cycle of storms because that is something the convection parametrization scheme used is unable to do. The timing of the larger-scale dynamical forcing may be largely independent of resolution.

Convective rainfall in the 12km forecasts has a tendency to trigger too early and then follow the daytime heating. For these cases, that did not present a problem, since the peak rainfall occurred during the afternoon (strong solar heating) in all the events. The heaviest rain from the mesoscale model 12km forecasts fell within the correct period of time in most of the forecasts although it started too soon by an hour or two on some occasions.

The high-resolution forecasts also generated the heaviest rainfall over the correct periods in all four cases. However, the 1km forecasts had a tendency to develop showers too early in the Wittering case and in one of the Hawnby forecasts. This did not result in the timing of the period of heaviest rain being wrong, but may have resulted in rain that was too widespread and not focussed enough.

Skill criterion 4 – Producing the rain over the correct area (extensiveness)

Predicting the correct location of the high totals is a notable achievement, but may not be particularly useful for flood warning if the extent of the rain area is wrong. The catchment-average accumulations are more important than the peak totals.

The operational 12km forecasts generated rainfall total that were too low over too wide an area. The forecasts would have generally only been useful for large river catchments.

The high-resolution forecasts showed contrasting behaviour. The 4km model was able to produce high totals on length scales that were observed by radar. When averaged to 12km squares the 4km forecasts gave accumulations in line with radar. However, this was sometimes at the expense of unphysical-looking systems and too many false alarms. The 1km model

tended to produce its highest totals over too small an area in all of the cases. For example, in the Boscastle case the totals over 50mm in the correct catchment covered only over a few grid squares. It also tended to produce low totals over too widespread an area. This behaviour appears to be due to a tendency to generate too many small showers and needs further examination.

7.2 Results from the orographic enhancement case (Carlisle flood).

The challenge to NWP models when predicting this type of event is reproducing the 'seeder feeder' mechanism and having an accurate enough representation of the orography so that the rainfall rates are correct in magnitude and relation to the orography.

The two critical elements of forecast skill are:

1. Producing the correct rainfall totals
2. Producing the rain over the correct area

In this case, the operational 12km model appears to have under-predicted the amount of rain when compared to radar and gauges. The 4km and 1km forecasts produced more rain. The 1km forecast produced the most and is thought to be the most accurate, but it is difficult to verify because of the inclusion of 12km model information in the radar measurements.

The operational 12km model tended to produce the rain over too widespread an area in line with its smoothed orography. The 4km and 1km models produced what is thought to be a more accurate forecast of the spatial distribution of the rainfall. The 1km forecast in particular generated much higher totals in the river catchments that fed into Carlisle. Verification is difficult for this type of event, but it does appear that the 1km model gave a better prediction.

7.3 What next?

The findings of this report have shown that, for these extreme events, a ~1km model is capable of producing high rainfall accumulations which are comparable to those observed. It is also capable of producing the high totals in the correct location. Of course, the accuracy of the forecasts varied and all of the forecasts could have been be better. Some of the deficiencies have been mentioned. The challenge is to see if it is possible to produce forecasts that much more closely resemble what happened to the extent that they could be used for accurate flood warning. This means performing suitable experiments to obtain a more detailed understanding of the important meteorological processes and how well the model represents those processes. After that, further sensitivity studies should provide insight into the predictability of these types of events using a storm-resolving model. Objective scale-selective verification methods are available for quantifying forecast skill.

The next stage involves choosing two of these cases for further study. All of them appear to be suitable.

8 References

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